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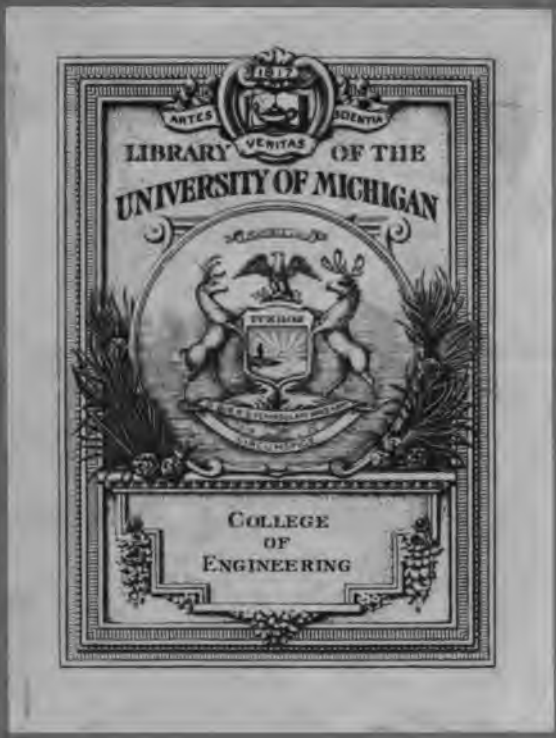
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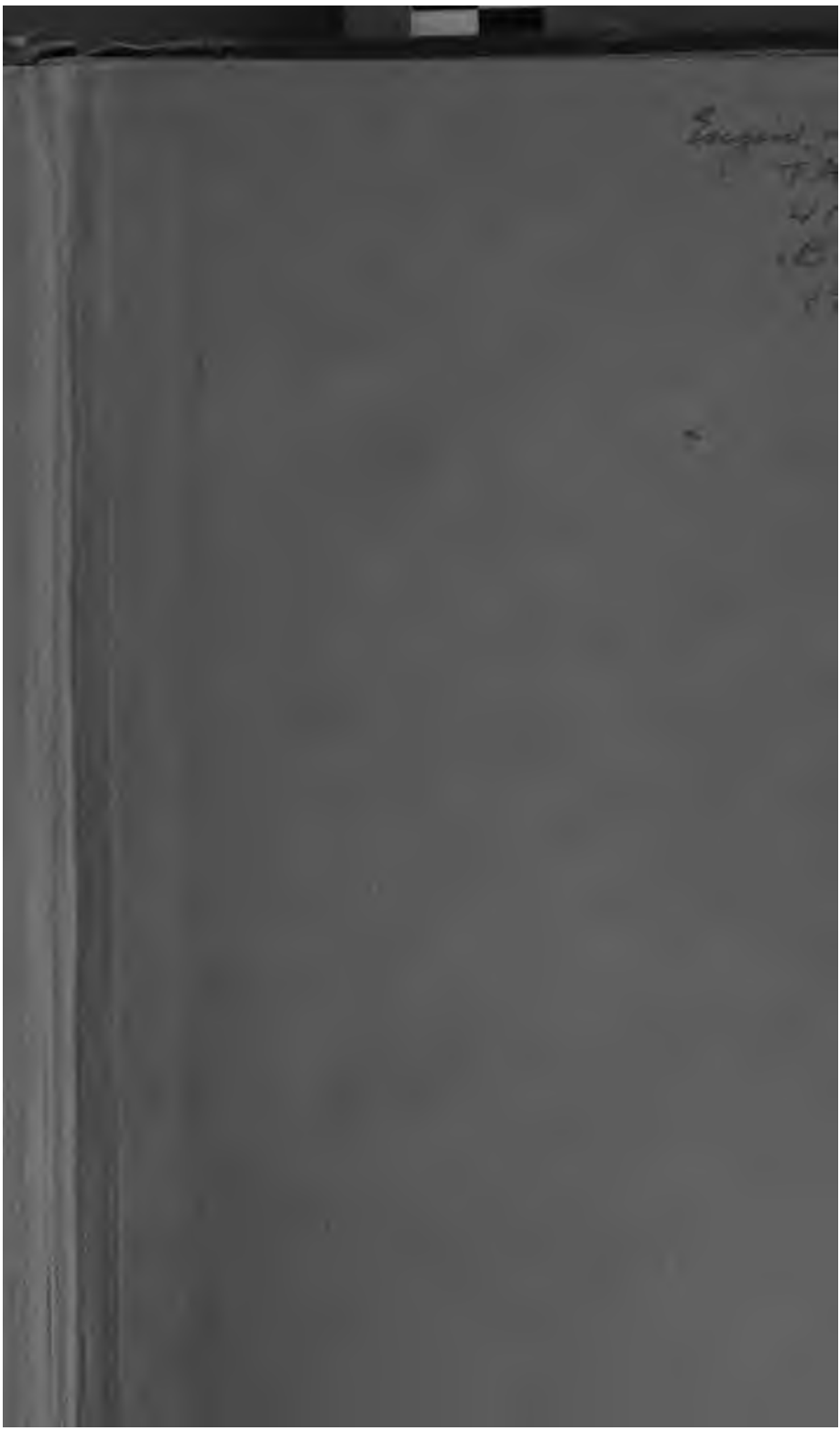

MECHANICAL TESTING

MECHANICAL TESTING

VOL. II.

THE SECOND VOLUME IS
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DURING THE SPRING OF
1922

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MECHANICAL TESTING

A TREATISE IN TWO VOLUMES

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VOLUME I.
TESTING OF MATERIALS OF CONSTRUCTION

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EDITORIAL NOTE

THE DIRECTLY-USEFUL TECHNICAL SERIES requires a words by way of introduction. Technical books of the have arranged themselves largely under two sections: Theoretical and the Practical. Theoretical books have b written more for the training of college students than for supply of information to men in practice, and have been gre filled with descriptions of an academic character. Prac books have often sought the other extreme, omitting the scien basis upon which all good practice is built, whether discern or not. The present series is intended to occupy a mid position. The information, the investigations, and the dis sions are to be of a directly-useful character, but must at same time be wedded to that proper amount of scientific expl tion which alone will satisfy the inquiring mind. We shall appeal to all technical people throughout the land, either stud or those in actual practice.

409693

AUTHORS' PREFACE

WITHIN the last few years the methods employed in the testing of materials of construction and the general mechanical testing of apparatus, structures and machines have undergone many important changes. The use of new instruments designed to imitate more closely the conditions under which the apparatus is employed in practice is gradually superseding the more approximate methods which have been adopted hitherto. The general trend of modern practice is to standardise testing arrangements in order, as far as possible, to eliminate the personal element and give a satisfactory basis for comparison of results.

The object of this book is to place before the Technical Engineer, Manufacturer and the Student the conditions governing modern testing, together with particulars of standard testing plant and its limitations, and such information as will enable the results obtained to be apprised at their true values.

It is hoped that the information given will be of real value to many and induce a desire for further research into the properties of the materials upon which all engineering design depends.

An endeavour has been made to refer to recent discoveries and improvements and mention in their proper places the authors responsible.

The present volume deals with the testing of materials of construction; it is hoped in the next volume to deal with the testing of apparatus, machines and structures.

Special thanks are due to Sir Richard Glazebrook, K.C.B., F.R.S., for kind permission to reproduce from his "Dictionary

of Applied Physics," certain sections of the present volume originally written for the Dictionary; to the Executive Committee of the National Physical Laboratory for permission to write the book, to the various firms who have so kindly supplied information as to their standard apparatus, and to Mr. J. L. Bale and the Engineering Staff of the National Physical Laboratory who have greatly helped with criticism and advice.

R. G. BATSON.
J. H. HYDE.

TEDDINGTON,
MIDDLESEX.

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CHAPTER I.

INTRODUCTORY.

(NOTE.—*The index figures in the text allude to the references, a list of which is given at the end of each chapter.*)

§ 1. IN engineering work, even from the early ages, the question of the best distribution of the material to give the greatest strength has been considered to some extent, but it is only comparatively recently that it has been necessary to reduce the dimensions of a structure as much as possible consistent with its safety.

This procedure has necessitated the testing of structures and materials in order to provide the designer with information that will enable him to use those materials to the best advantage.

The method which gives the most direct information is a test to destruction of the completed structure. A test of this nature, however, is usually very costly, and is seldom carried out. A proof test is, however, often used, and consists in subjecting the structure to a load slightly greater than that which it will afterwards be called upon to stand. This gives to some extent an idea of the safety of the structure and an indication of any unsuspected weakness, but care has to be taken to ensure that the method of loading and the distribution of the loads is of the same kind as are met with under working conditions. It is well known that a structure will fail under a much smaller load, repeated many times, than that which will break it by a single loading.

By making certain assumptions we can calculate from theoretical considerations the loads to which parts of structures are subjected.

The designer, in order to proportion the parts of his machine or structure and apply his theoretical calculations, requires to know the physical constants of the materials with which he deals. The aim of the scientific experimenter is to supply this data in order that the theoretical researches in applied mechanics may be applied to the problems with which we are confronted in engineering practice. Absolute results concerning definite properties of materials form the basis of *scientific testing*.

The material to be used in the construction of the machine can usually be obtained from several sources of supply and of several grades and prices. The engineer wishes first to indicate to the manufacturer the class of material he needs, and for this purpose he supplies him with a specification containing among other things particulars of the properties required. The design is based on certain values of the physical constants, and these values are the real criterion of the suitability of the material for the purpose for which it is intended. The determination of the constants is usually a slow, laborious business requiring considerable skill and scientific ability. Approximate tests have been devised, in some cases approximating closely to the scientific tests, which are only intended to give a comparative indication of the physical properties of the material. The results expected from these tests are inserted in the specification.

It is, obviously, important for the engineer to be assured that the material supplied fulfils the terms of the specification, and for this purpose he selects sample portions of the material and subjects them to the specified tests. *Commercial testing* is therefore carried out to determine whether materials conform to the terms of specifications.

There is a further section of the subject which has been given a great impetus in the last few years, viz. *investigatory testing*, undertaken either to determine causes of failure of material in actual practice or to improve processes of manufacture and design of machines and structures.

The science of engineering is advanced by a systematic study of failures probably quite as much as by any other branch of research. In investigatory testing, methods are employed to exaggerate certain properties in order to compare them in various materials with ease and certainty. These same properties can probably be studied by a careful analysis of the absolute results obtained by scientific testing, but the process is difficult and cannot be attended with success without considerable practical experience.

CHAPTER II.

LOAD, STRAIN, STRESS, AND ELASTICITY.

§ 2. THE equilibrium of a machine or structure requires that certain conditions shall be fulfilled :—

(i) The forces which external bodies exert on the *whole* machine or structure must balance each other.

(ii) The external forces acting on any part of the machine or structure must balance each other. This condition must be fulfilled whether the part under consideration is a series of links, a single link, or a part of a link.

The load is the combination of external forces applied to any part of the machine under consideration and is designated by the method of its application.

(*a*) *A dead load* is one which is steady or invariable, such as the weight of the fixed part of a machine or a gradually applied load as in a testing machine.

(*b*) *A live load* is one which is alternately applied and removed, such as the weight of traffic passing over a bridge.

(*c*) *A suddenly applied load* is one which is placed on the machine at one instant. It may be applied with or without shock, in the former case it is sometimes called an *impulsive load.*

Every load, no matter how small, which acts on a body produces an alteration of dimensions or form. This deformation is called *the strain.* A dead load produces a strain of definite and unvarying amount, a live load gives a constantly varying strain, while a suddenly applied load increases the strain beyond the amount due to the same load steadily applied.

A body is composed of a number of minute particles which are held together by molecular attraction and are kept apart by repulsion. External load produces changes in the molecular actions within the body, and the resistance to these changes is called *the stress.* When this resistance is called into play the body is said to be in a *state of stress.* Thus the external load produces strain which calls stress into play. The determination

of the relationship between strain and stress in materials is one of the principal objects of scientific testing.

Strain is measured by a mere number, load and stress are both measured in units of force. It is generally assumed that, in most cases, the conditions applying to loads hold for stresses.

The *intensity of stress* is the stress per unit area, thus a stress of " P " tons acting on an area of " A " square inches is equivalent to an intensity of stress of " P/A " tons per square inch. The distribution is said to be uniform when every fraction of the area bears a corresponding fraction of the whole load or stress.

Elasticity is that property by virtue of which a material tends to recover its original shape and dimensions when the straining force is withdrawn. A material is said to be *perfectly elastic* to any external load if the strain disappears when the load is removed. Under these conditions the strain is called " elastic strain ".

Plasticity is the state or quality of being deformed into various shapes. A *perfectly plastic* material is one which can undergo an indefinitely large permanent deformation. The strain thus produced is called " plastic strain ".

Some materials when subjected to an increasing load at first behave elastically but afterwards begin to flow and alter their shape. A value of the load is reached which produces a strain which persists when the straining force is removed. The material is said to be " imperfectly elastic " at that load and the permanent change of form is called permanent strain or permanent set.

§ 3. **Elastic Limits.**—The " primitive " elastic limit or " primitive " limit of elasticity is the maximum stress which the material can undergo without receiving a visible permanent set. Most materials on loading for the first time show small sets within the elastic limit, but these may be due to want of homogeneity of the material or initial curvature of the bars tested. The elastic limit is said to be " primitive " to distinguish it from those limits which are obtained after the material is subjected to cyclical variations of the stress. These are called the " natural " elastic limits and may be defined as the maximum stresses the material will bear when applied continuously or repeated indefinitely without giving an increasing strain.

Hooke's Law.—Within the limits of elasticity, stress is proportional to strain. This relationship was first stated by Robert Hooke in 1676 and refers to all kinds of strain and stress.

§ 4. **Elastic Modulus.**—From Hooke's Law it follows that, if

f = intensity of stress
e = strain
then f/e = constant
or f = constant × e.

The constant in this equation is called the Elastic Modulus or Coefficient of Elasticity.

For each kind of stress and strain there is a different kind of modulus the value of which varies according to the material employed. The elastic modulus can therefore be taken as a standard for comparing the relative elasticity of different materials.

As strain is a quantity which is simply a number, the modulus has the same dimensions as an intensity of stress. The material which has the smallest value for the modulus of elasticity is the most elastic.

The kind of strain and stress which exists in any part of a structure or machine depends upon the direction and arrangement of the forces external to that part.

§ 5. **Methods of Loading.**—The elementary methods of loading are :—

(i) Direct or normal loading.

(a) Tension producing tensile strain (extension or elongation) and tensile stress.

(b) Compression producing compressive strain and compressive stress.

(ii) Tangential loading or shear producing shear strain and shear stress.

The loading of a body produces, in general, both direct and shearing stresses. It is only on certain sections in the body that the stresses will be only either direct or shear.

§ 6. **Direct or Normal Loading.**—(a) **Tension.**—Tension is a direct pull along the axis of a body. The simplest example of a material subjected to tension is a tie bar or tie.

Fig. 1 represents a tie under a tensile load (P) acting along the axis of the tie. Now consider the effect of the load on any section XY (area = A) at right angles to the axis and enlarge this section as in Fig. 2 so that "ab" is really an infinitely small length. The tensile load (P) acts outwards ← → tending to pull the body apart at the section XY. The stress in the body at XY resists the load and therefore acts in the opposite direction → ← drawing the parts together. The mean intensity of stress (f_t) on section XY = P/A. The tensile load causes an extension

in length and diminution of cross section of the tie (indicated in Fig. 1 by dotted lines). If

the original length of the tie = L
and the length after loading = L_1
then the extension (x) = $L_1 - L$

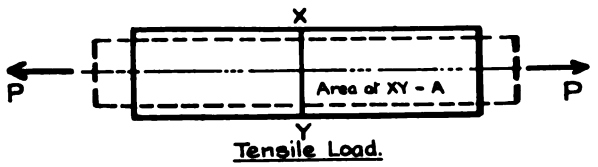


FIG. 1.

and the extension per unit length or tensile strain

$$(e_t) = \left(\frac{L_1 - L}{L}\right)$$

and the percentage tensile strain = $\left(\frac{L_1 - L}{L}\right) \times 100$.

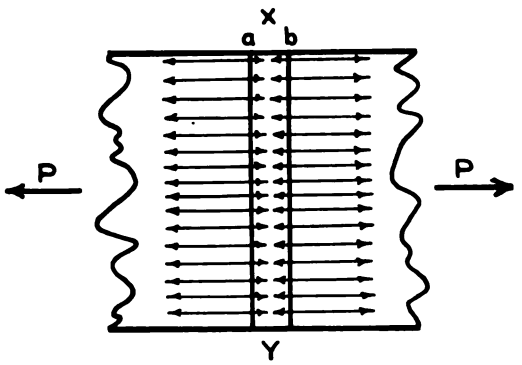


FIG. 2.

(*b*) **Compression.**—Compression is a direct push along the axis of a body. It is therefore of opposite sign to tension and is sometimes considered as a negative tension.

The compressive load (P, Fig. 3) acts inwards → ← and tries to crush the body, the stress in the body resists this crushing action and therefore acts outwards thus ← →.

Compression causes a contraction in the length and an increase in the cross section.

If L = the original length and
L_1 = the length after loading

then the compressive strain (e_c) = reduction in length per unit length

$$= \frac{L - L_1}{L}$$

and percentage compressive strain $= \left(\frac{L - L_1}{L}\right) \times 100.$

By Hooke's Law (§ 3)

intensity of stress = constant × strain
i.e. for tension $f_t = E \times e_t$
for compression $f_c = E \times e_c$

where f_t = tensile stress intensity
f_c = compressive stress intensity
e_t = tensile strain
e_c = compressive strain
E = modulus of direct elasticity or Young's Modulus.

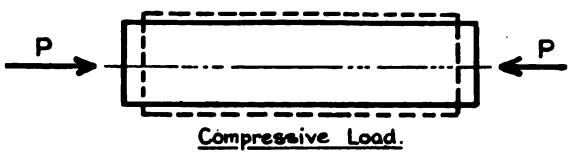


FIG. 3.

The modulus of direct elasticity is sometimes considered as the intensity of stress when the material is deformed an amount equal to its original length, assuming that it behaves elastically up to that point.

§ 7. **Poisson's Ratio.**—When a bar is subjected to direct loading it extends or compresses longitudinally and contracts or dilates transversely. The ratio of the transverse change to the change longitudinally is called Poisson's Ratio and is denoted by $1/m$. Within the elastic limit the value of m is constant for a given material and generally has a value between 3 and 4.

If $\pm e$ is the longitudinal strain then the lateral strain or dilation $= \pm e/m$,
if L = the original length of a bar
and A = the original cross sectional area of the bar ;
after the bar is loaded L becomes L $(1 + e)$
and A becomes A $(1 - e/m)^2$.

the original volume of the bar = AL
the final volume of the bar = $AL(1 + e)(1 - e/m)^2$
$= AL(1 + e - 2e/m)$ approx.

Therefore the alteration of unit volume = $e - 2e/m$, and if $m = 4$ (as for most metals) this = $e/2$.

For india-rubber, where $m = 2$, there is no change of volume.

§ 8. **Tangential Loading or Shear.**—When a body is loaded so that there is a tendency for one part to slide on the next, the stress induced in the material is a shear stress. The loading is tangential or parallel to the section under consideration.

Shear stress may also be defined as that stress which is pro-

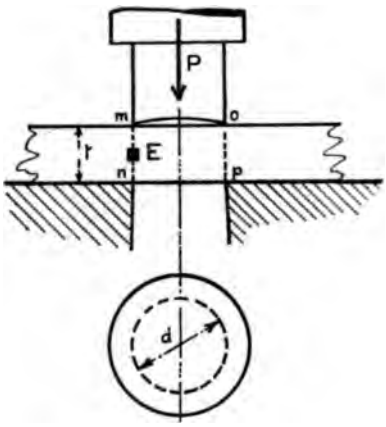


FIG. 4.

duced in a body by a tensile and compressive stress of equal amounts at right angles to each other.

Shear may be treated under three distinct divisions :—

(*a*) Uniformly distributed shear over a particle.

(*b*) Shear varying in intensity from zero at the surface to a maximum at some point within the section whose position depends upon the form of the section (Shearing force in a beam).

(*c*) Shear varying in intensity from a maximum at the surface to zero at the centre (Torsion).

Simple Shear.—An illustration of simple shear is given by the operation of punching a hole in a piece of plate (Fig. 4). When the punch exerts a pressure P a shear stress is induced in the material on the area shown circular in plan (diam. = *d*) and by the lines *mn* and *op* in elevation.

The area resisting the shearing load is therefore $= \pi d \times t$ and the intensity of shear stress (f_s), which is uniformly distributed at all parts of the section, is equal to $P/\pi dt$.

A rivet connecting three plates (as in Fig. 5) is usually in pure shear when subjected to a pulling (or pushing) force P acting along the axis of the centre plate.

The shear in this case is taken on the two sections X_1Y_1 and X_2Y_2 and the rivet is said to be in double shear.

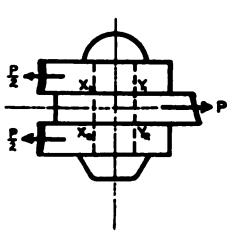


FIG. 5.—Rivet in double shear.

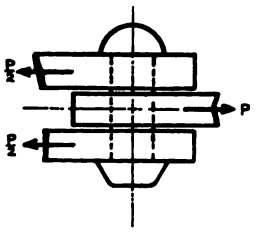


FIG. 6.

If the combined area of the two sections (X_1Y_1 and X_2Y_2) = A then the intensity of shear stress (f_s) = P/A.

Should the plates not be riveted together tightly the rivet acts as a beam as shown exaggerated in Fig. 6 and the stress is not pure shear.

§ 9. **Shear Stresses in Planes at Right Angles.**—If E (Fig. 4) is a rectangular particle of material under simple shear and we draw an enlarged view of one rectangular side as shown in Fig. 7 then there is a shear stress intensity of f_s along the sides AD and CB. These two forces form a couple and for equilibrium must be balanced by an equal and opposite couple. Assume a balancing couple along the sides CD and AB with a shear stress intensity of f_s'. If the block is taken to be one unit thick perpendicular to the paper, then the total shear stresses on the faces AB, BC, CD, and DA are $f_s' \times AB$, $f_s \times BC$, $f_s' \times CD$, and $f_s \times AD$ respectively.

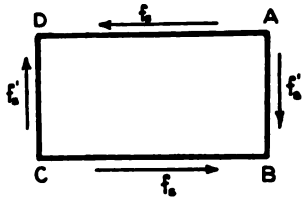


FIG. 7.

By equating the moments of the two couples we get

$$f_s \times AD \times AB = f_s' \times AB \times AD$$

or

$$f_s = f_s'$$

That is: an intensity of shear stress on any two parallel

planes is accompanied by an equal intensity of shear stress on two parallel planes at right angles to them.

§ 10. **Shear Strain and Modulus Rigidity.**—If we now consider that the particle E (Fig. 4) under simple stress is a cube and draw an enlarged view of it as shown in Fig. 8, the shearing force will distort the cube into a prism and a face ABCD will become AB_1C_1D.

AB is deflected through an angle θ to AB_1 and this angle in radians is a measure of the shearing strain. As the amount of movement, within the elastic limit, is very small θ can be taken as equal to $\tan \theta = BB_1/AB$.

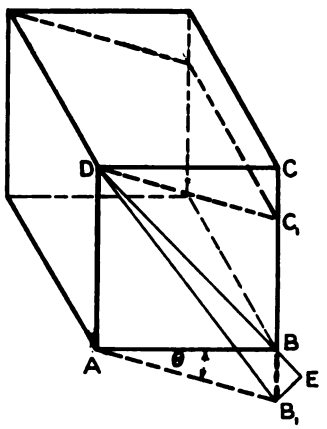


FIG. 8.

By Hooke's Law, shear stress = constant × shear strain.

i.e. $$f_s = C \times \theta.$$

C is the shearing modulus, modulus of rigidity or modulus of transverse elasticity.

Diagonal DB (still referring to Fig. 8) increases in length to DB_1.

If B_1E is drawn perpendicular to DB produced, meeting it in E, B_1E can be considered as coinciding with the arc centered at D so that the linear strain or extension per unit length

$$= \frac{DB_1 - DB}{DB} = \frac{BE}{DB} = \frac{BB_1/\sqrt{2}}{AB \times \sqrt{2}} = \tfrac{1}{2}\frac{BB_1}{AB} = \tfrac{1}{2}\theta.$$

Similarly there is a reduction in the length of the diagonal AC to AC_1 and the amount of the shortening $= -\tfrac{1}{2}\theta$. That is

to say the strains along the diagonals of the face of a cube subjected to shearing are each half of the shear strain.

§ 11. **Tangential and Normal Components of Oblique Stresses.**—Let Fig. 9 represent a bar (area A) under a stress = P. The intensity of stress on a normal section (XY) = P/A = p. Consider an oblique section EF, making an angle of (90° − θ) with the axis of the bar.

The stresses on this section consists of :—

(*a*) A stress of intensity p_t acting tangentially and causing sliding at the section.

(*b*) A stress of intensity p_n acting perpendicular or normal to the section.

These stresses can be determined by resolving the stress P into its tangential and normal components.

In this case :—

The tangential stress intensity

$$(p_t) = \frac{P \sin \theta}{\text{area of section EF}}$$

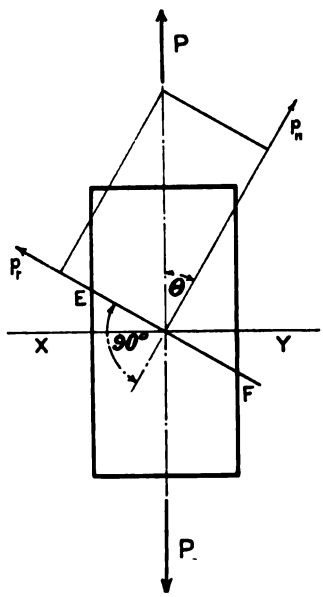


FIG. 9.

$$= \frac{P \sin \theta}{A \sec \theta} = \frac{P}{A} \sin \theta \cos \theta = p \sin \theta \cos \theta = \frac{p}{2} \sin 2\theta$$

therefore p_t is a maximum when $2\theta = 90°$ or $\theta = 45°$ and the maximum value = $p/2$.

The normal stress intensity $(p) = \dfrac{P \cos \theta}{\text{area of section EF}}$

$$= \frac{P \cos \theta}{A \sec \theta} = \frac{P}{A} \cos^2 \theta = p \cos^2 \theta.$$

§ 12. **Combination of two Simple Pushes or Pulls in Directions at Right Angles to each other.**—Let ABCD (Fig. 10) represent a cube of unit side with simple stresses of intensities p_x and p_y normal to the two pair of faces.

Consider the plane EF making an angle of θ with the direction of p_y.

Resolving normally to EF we have

$$p_n = \frac{p_x \cos\theta}{\sec\theta} + \frac{p_y \sin\theta}{\operatorname{cosec}\theta} = p_x \cos^2\theta + p_y \sin^2\theta$$

and for $\theta = 45°$, the normal stress is a maximum and $= p_x/2 + p_y/2$.

Resolving tangentially to EF we have

$$p_t = \frac{p_x \sin\theta}{\sec\theta} - \frac{p_y \cos\theta}{\operatorname{cosec}\theta} = p_x \sin\theta\cos\theta - p_y \cos\theta \sin\theta$$

$$= (p_x - p_y)(\cos\theta \sin\theta) = (p_x/2 - p_y/2) \sin 2\theta$$

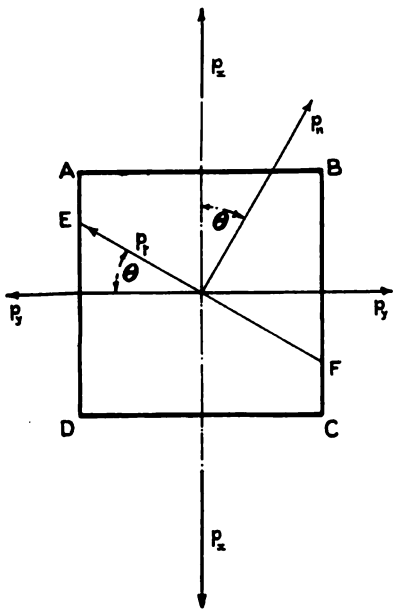


FIG. 10.

as before this is a maximum for $\theta = 45°$ in which case

$$p_t = p_x/2 - p_y/2$$

when $p_x = p_y$, but is opposite in sign, on planes at 45° p_n = O and p_t (the shear stress) $= p_x = p_y$. That is to say—simple shearing stress is equivalent to pure tensile and compressive stresses at right angles and inclined at 45° to the plane of pure shear. The intensities of the three stresses are equal to each other.

§ 13. **Relation between the Modulus of Direct Elasticity and the Modulus of Transverse Elasticity.**—The strain in the diagonals of a cube of material ABCD (Fig. 8) under a simple shear stress (f_s) is seen (§ 10) to be half the shear strain and therefore $= \frac{f_s}{\frac{1}{2}C}$ (because shear stress = C × shear strain, see § 10). This simple shearing stress (f_s) is equivalent to a direct tensile stress (f_t) along one diagonal (AC) combined with a direct compressive stress (f_c) of equal intensity along the diagonal (DB) at right angles to it (§ 12), and $f_s = f_t = f_c$.

The tensile stress causes a strain in AC $= f_t/E$, and a strain in DB $= -f_t/mE$, where $1/m =$ Poisson's Ratio (§ 7) and tensile stress = E × tensile strain.

The compressive stress causes a strain in AC $= f_c/mE$ and a strain in DB $= -f_c/E$,

i.e. the total strain in diagonal AC $= \frac{f_t}{E} + \frac{f_c}{mE}$.

And, as $f_t = f_c = f_s$, this equals $\frac{f_s}{E} + \frac{f_s}{mE} = \frac{f_s}{E}\left(1 + \frac{1}{m}\right)$

but the strain in the diagonals also equals $f_s/2C$ (see § 10).

Therefore $$\frac{f_s}{E}\left(1 + \frac{1}{m}\right) = \frac{f_s}{2C}$$

or $$\frac{1}{E}\left(1 + \frac{1}{m}\right) = \frac{1}{2C}$$

i.e. $$E = 2C\left(1 + \frac{1}{m}\right) \text{ or } \frac{1}{m} = \frac{E - 2C}{2C}.$$

For steel, where $m = 4$, we have $E = 2{\cdot}5\ C$.

§ 14. **Volumetric Modulus of Elasticity.**—When a body is subjected to external forces all round it (such as are due to total immersion in a liquid) there is a slight reduction in the volume. The unit change of volume is the volumetric strain (e_v) and, within the limits of elasticity, the intensity of normal stress

$$= f = K \times e_v \quad \ldots \text{ equation 1,}$$

where K is a constant for the material called the volumetric modulus of elasticity or the bulk modulus.

If we consider (Fig. 11) a cube of unit side, subjected to pressure on each of its sides of intensity $= p$, the force parallel to edge CB causes a shortening of that edge by an amount $= p/E$.

Each of the two pairs of forces at right angles to CB cause a lengthening of amount $= p/mE$, so that the total linear strain on CB equals

$$e = p/E - 2(p/mE) = \frac{p}{E}\left(1 - \frac{2}{m}\right).$$

The linear strain of each of the other edges is the same, therefore = the volumetric strain $(e_v)\left\{1 - \left[\frac{p}{E}\left(1 - \frac{2}{m}\right)\right]^3\right\} - 1$, and as the linear strain within the elastic limit is very small

$$e_v = 3 \times \frac{p}{E}\left(1 - \frac{2}{m}\right) \text{ approximately,}$$

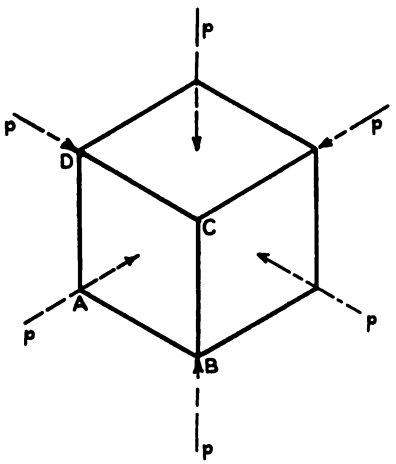


FIG. 11.

but $e_v = f/K$ (see equation 1) and $f = p$,

therefore $$\frac{1}{K} = \frac{3}{E}\left(1 - \frac{2}{m}\right) \text{ or } K = \frac{1}{3}\left(\frac{m}{m-2}\right)E$$

but $$1/m = \frac{E - 2C}{2C} \text{ (see § 13)}$$

therefore $$1/K = \frac{3}{E}\left\{1 - \frac{E - 2C}{C}\right\} \text{ or } K = \frac{EC}{9C - 3E}$$

$$C = \frac{3EK}{9K - E}$$

$$E = \frac{9KC}{C + 3K}.$$

§ 15. **Principal Stresses and Planes of Principal Stress.**—In Fig. 12, suppose that across the section CA (at right angles to the paper) we have a normal stress of intensity p and a shear stress of intensity q. The shear stress on CA is accompanied by equal and opposite shear in the face DC at right angles to it (see § 9).

The problem is to find the stress (f) on the face DA on which we assume that the stress is normal only.

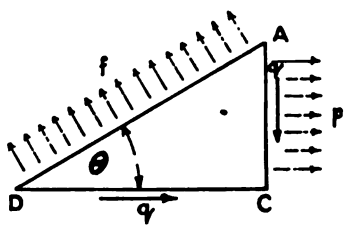


FIG. 12.

Resolving horizontally we have

$$f \times AD \times \sin\theta = p \times AC + q \times DC$$

$$\text{i.e. } f \sin\theta = p\frac{AC}{AD} + q\frac{DC}{AD}$$

$$= p \sin\theta + q \cos\theta$$

$$\text{or } f = p + q \cot\theta \quad . \quad . \quad . \quad (1)$$

Resolving vertically $q \times AC = f \times AD \times \cos\theta$

$$q \sin\theta = f \cos\theta$$

$$q = f\cot\theta \text{ or } \cot\theta = \frac{q}{f} \quad . \quad (2)$$

Substituting equation (2) in equation (1) we have

$$f = p + \frac{q^2}{f} \text{ or } f^2 - pf - q^2 = 0$$

or

$$f = \frac{p}{2} \pm \sqrt{\frac{p^2}{4} + q^2}$$

f then is the normal stress on a plane on which there is no tangential stress, and is therefore a principal stress. There are two values of "f" and these correspond to the two values of the principal stress and act on planes at right angles to each other, called the planes of principal stress.

§ 16. **Theory of Bending.**—In order to determine the relationship between strain, stress, elasticity, deflection, etc., in a beam, under simple bending, certain assumptions are necessary, viz. :—

(*a*) The beam is symmetrical about a certain longitudinal plane and is subject to only transverse loading in this plane. The plane is called the principal plane of bending.

(*b*) The beam is initially straight.

(*c*) The material is homogeneous and perfectly elastic.

(*d*) The material follows Hooke's Law, notwithstanding the lateral connection of the layers.

(*e*) The modulus of elasticity is the same in tension as in compression.

(*f*) Transverse sections which were plane before bending remain plane after bending.

A beam need not necessarily be horizontal, in some structures tie bars or struts have transverse forces acting on them as well as longitudinal ones. In the majority of cases, however, beams are horizontal, the loads act vertically downwards and are supported by upward forces.

§ 17. **Nature of the Stresses in a Beam.**—For a beam to be under simple bending there must not be any shearing forces present. Such a case is the part of the beam between the points of support in Fig. 13 A where equal couples are applied to the two ends. If the beam is assumed to be without weight and is cut transversely between A and B in order to maintain equilibrium it will only be necessary to introduce a pair of equal horizontal forces—a tension T and a thrust C—on either cut surface (Fig. 13 B) having a moment ($Th = Ch$) equal and opposite to that of the external forces ($Wl = Rl$).

The moment of the external forces (Wl) is called the Bending Moment.

If the beam is cut, however, at a section XY between B and D (Fig. 13 C) a vertical force S is required equal to W as well as the couple T_1h to balance the moment Wl_1 of the load W. That is, there is a shearing stress at the section XY as well as tensile and compressive stresses.

The shearing force at any section of a beam is equal to the algebraic sum of all the external forces on one side of the section.

The bending moment at any section is equal to the sum of all the moments of the external forces on one side of the section.

§ 18. **Position of the Neutral Axis and Intensity of the Longitudinal Stress.**—If we consider a small section EF of the beam in Fig. 13 A after bending whose length is δx, and enlarge this as in Fig. 14 the sides KL and MN when produced meet in O. Let the radius OE = R. The top part of the section is in tension and the under part in compression. Some layer, called the neutral surface, between the two will remain unaltered in length. Let the neutral surface be EF and consider an elementary strip δy situated at a distance y from it.

The strain of this strip $= \dfrac{\text{extension}}{\text{original length}} = \dfrac{PQ - EF}{EF}$.

By similar triangles $\dfrac{PQ}{EF} = \dfrac{R + y}{R}$.

Therefore strain $= \dfrac{R + y - R}{R} = \dfrac{y}{R}$

f = the intensity of stress = E × strain = $\dfrac{E \cdot y}{R}$

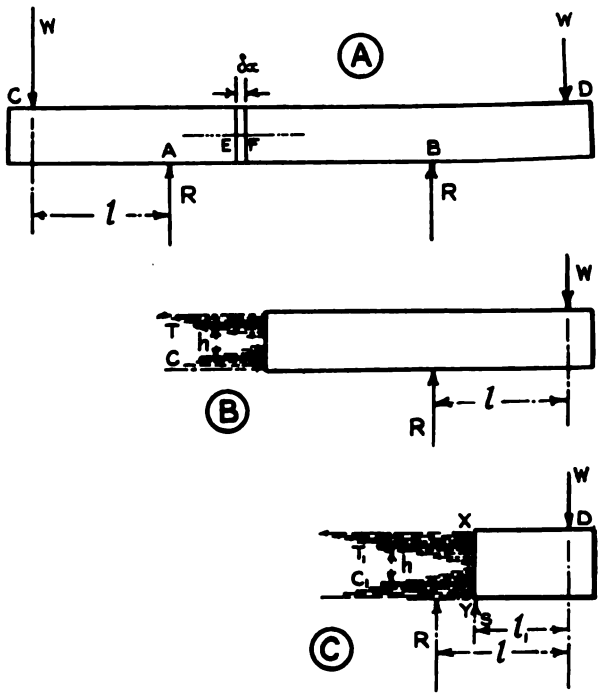


FIG. 13.

or $\dfrac{f}{y} = \dfrac{E}{R}$ . . . equation (1)

Let the beam have a width = b, then the stress (total) acting on the elementary strip of thickness δy

$= f \times b \times \delta y = \dfrac{Ey}{R} b \cdot \delta y$. equation (2)

Summing up all the stresses on all the strips over the whole section—

the stress (total) on the section $= \frac{E}{R}\Sigma by \,.\, \delta y$. equation (3)

As the section is in equilibrium there is no resultant force

therefore $$\frac{E}{R}\Sigma by \,.\, \delta y = 0$$

i.e. Σ(each elementary area × its distance from the neutral surface) = 0; therefore the neutral surface passes through the centre of gravity of the section.

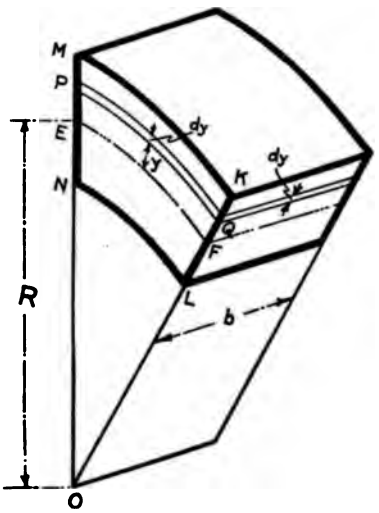


FIG. 14.

The bending moment at the section = the moment of resistance of the section = the sum of moments of the stresses on the section about the neutral surface.

By equation (2) the stress (total) on the elementary strip (Fig. 14)

$$= \frac{Ey}{R} b \,.\, \delta y.$$

The moment of this stress about the neutral surface

$$= \left(\frac{Ey}{R} b \,.\, \delta y\right) \times y.$$

Therefore the total moment $= \frac{E}{R}\Sigma b \cdot y^2 \cdot \delta y = \frac{E}{R}\Sigma$ (each elementary area $\times$ **the square** of its distance from the neutral surface) $= \frac{E}{R}$ multiplied by the second moment or moment of inertia;

i.e. bending moment $(M) = \frac{E}{R}I$

or $$\frac{M}{I} = \frac{E}{R} = \frac{f}{y}$$ from equation (1)

$$M = \frac{fI}{y} = fZ$$ equation (4)

where $Z = \frac{I}{y}$ = modulus of the section.

If f_t and f_c are the tensile and compressive intensities of stress at distances y_t and y_c from the neutral surface

then $$M = \frac{f_t I}{y_t} = f_t Z_t$$

and $$M = \frac{f_c I}{y_c} = f_c Z_c$$

f_t and f_c have their greatest value where y_t and y_c are the distances from the neutral surface of the extreme layers on the tension and compression sides respectively.

It is necessary to emphasise the fact that these formulæ are only true when the assumptions made in the theory are carried out. Thus, if equation (4) is used to find stresses above the limit of proportionality of stress to strain, i.e. when the stress is so great that Hooke's Law no longer holds, the results will be untrue.

Values of the moment of inertia and modulus of section for several simple forms of section are given in Table I.

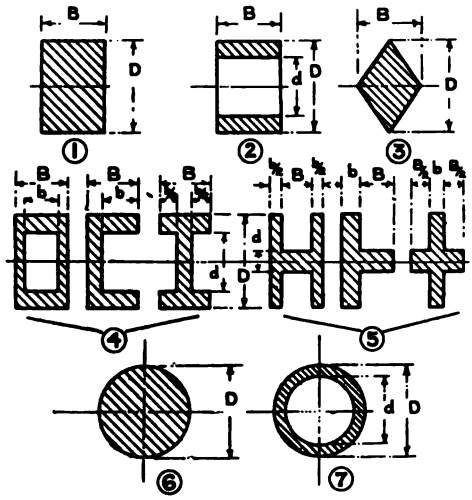
§ 19. **Deflection.—Uniform Curvature.**—In simple bending the beam is under uniform bending moment and bends into the arc of a circle. If ABC (Fig. 15) is such a beam, whose span is x, deflection y and radius of curvature $R\left(\frac{I}{R}\right.$ is called the curvature of the beam),

then $$(R - y)^2 + (x/2)^2 = R^2$$

or $$2Ry - y^2 = x^2/4$$

TABLE I.

VALUES OF THE MOMENT OF INERTIA AND MODULUS OF SECTION OF SIMPLE FORMS OF SECTION.



Form of Section.	Area.	Moment of Inertia. (I).	Modulus of Section. (Z).
(1)	BD	$\frac{1}{12} BD^3$	$\frac{1}{6} BD^2$
(2)	$B(D - d)$	$\frac{1}{12} B(D^3 - d^3)$	$\frac{1}{6} \cdot \frac{B}{D} (D^3 - d^3)$
(3)	$\frac{1}{2} BD$	$\frac{1}{48} BD^3$	$\frac{1}{24} BD^2$
(4)	$BD - bd$	$\frac{1}{12} (BD^3 - bd^3)$	$\frac{1}{6} \left(\frac{BD^3 - bd^3}{D} \right)$
(5)	$bD + Bd$	$\frac{1}{12} (bD^3 + Bd^3)$	$\frac{bD^3 + Bd^3}{6D}$
(6)	$\frac{\pi D^2}{4}$	$\frac{\pi}{64} D^4$	$\frac{\pi}{32} D^3$
(7)	$\frac{\pi}{4}(D^2 - d^2)$	$\frac{\pi}{64} (D^4 - d^4)$	$\frac{\pi}{32} \left(\frac{D^4 - d^4}{D} \right)$

as y is very small within the limit of proportionality y^2 can be neglected and therefore

$$2Ry = x^2/4 \text{ or } y = \frac{1}{8} \times \frac{x^2}{R}.$$

Now $M/I = E/R$ (see § 18)

and the curvature $= \frac{1}{R} = \frac{M}{EI}$.

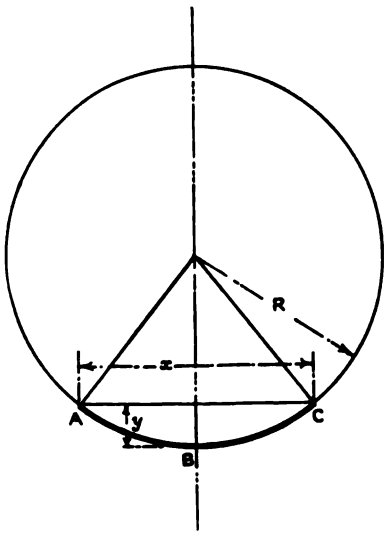


FIG. 15.

Therefore the deflection $= y = \frac{x^2}{8R} = \frac{Mx^2}{8EI}$

where

M = bending moment between the points of support A and C.
I = moment of inertia of the section of the beam.
E = modulus of direct elasticity.

§ 20. **General Relationship between Curvature, Slope, Deflection, etc.**—In cases where the loading of the beam produces a varying bending moment, the deflection at the centre $= K \times \frac{Mx^2}{EI}$ where K is less than 1/8.

The value of this constant for each method of loading can be obtained by a consideration of the general case.

Let A and B (Fig. 16) be two points which are very close together on the neutral surface of a beam.

Let the co-ordinates of the point B, with respect to some origin O, be x and y, and let the co-ordinates of point A from the same origin be $x + \delta x$ and $y + \delta y$.

The arc AB can be assumed to have a virtual centre C where BC = R = the radius of curvature.

The slope of the beam (i) with reference to the origin O, is the angle between the tangents to the curve at B and O and equals the rate of change of deflection with regard to distance $= dy/dx$.

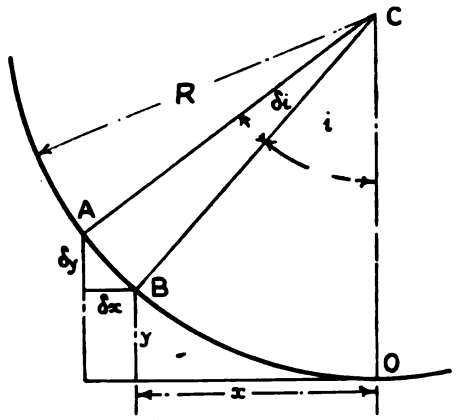


FIG. 16.

The increase in the slope of the beam between the points A and B = angle ACB (in radians) = δi

$$= AB/BC = AB/R.$$

Now the deflections are very small so that AB may be taken as equal to δx;

therefore $$\delta i = AB/R = \delta x/R$$

Curvature = $1/R = di/dx$ = rate of change of slope, but i (the slope) = dy/dx;

therefore curvature $$= 1/R = \frac{d^2y}{dx^2} = \frac{M}{EI} \quad \text{(see § 19)}$$

$$\text{slope} \quad (i) = \frac{dy}{dx} = \int \frac{M}{EI} dx.$$

$$\text{deflection} \quad = y = \iint \frac{M}{EI} dx \,.\, dx.$$

As an example consider the case of a beam of span = l loaded in the centre with a dead weight = W (Fig. 17).

The bending moment at section XY = $\frac{Wx}{2}$

the curvature $= \frac{d^2y}{dx^2} = \frac{M}{EI}$

Therefore $EI\frac{d^2y}{dx^2} = M = \frac{Wx}{2}$ . . equation (1)

Integrating we have $EI\frac{dy}{dx} = \frac{Wx^2}{4} + C$

where $x = l/2$ the slope $(dy/dx) = O$.

Therefore $Wl^2/16 + C = O$, or $C = -\frac{Wl^2}{16}$

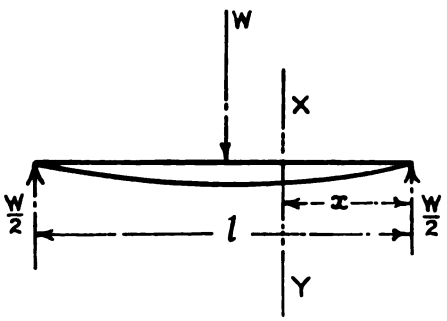


Fig. 17.

and $EI\frac{dy}{dx} = \frac{Wx^2}{4} - \frac{Wl^2}{16}$. . equation (2)

The slope is a maximum where $x = O$

therefore the maximum slope $= -\frac{Wl^2}{16EI}$.

Integrating equation (2) we get $EIy = \frac{Wx^3}{12} - \frac{Wl^2}{16}x + K$

where $x = O$, the deflection is O and therefore $K = O$.

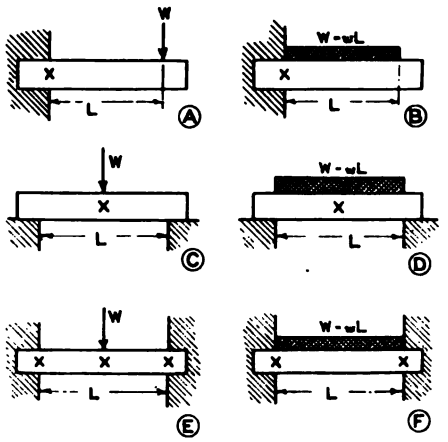
Therefore $y = \left(\frac{Wx^3}{12} - \frac{Wl^2}{16}x\right)\frac{1}{EI}$

and deflection (y) is a maximum where $x = l/2$;

therefore maximum deflection $= \left(\frac{Wl^3}{96} - \frac{Wl^3}{32}\right)\frac{1}{EI} = \frac{1}{48}\frac{Wl^3}{EI}$.

TABLE II.

VALUES OF SHEAR, BENDING MOMENT, SLOPE AND DEFLECTION FOR VARIOUS METHODS OF LOADING BEAMS AND CANTILEVERS.



Method of Loading.	Maximum Bending Moment at X.	Maximum Shearing Force.	Maximum Slope.	Maximum Deflection.
(A)	WL	W	$\frac{1}{2}\frac{WL^2}{EI}$	$\frac{1}{3}\frac{WL^3}{EI}$
(B)	$\frac{1}{2}WL$ or $\frac{1}{2}wL^2$	W	$\frac{1}{6}\frac{WL^2}{EI}$	$\frac{1}{8}\frac{WL^3}{EI}$
(C)	$\frac{1}{4}WL$	$\frac{1}{2}W$	$\frac{1}{16}\frac{WL^2}{EI}$	$\frac{1}{48}\frac{WL^3}{EI}$
(D)	$\frac{1}{8}WL$ or $\frac{1}{8}wL^2$	$\frac{1}{2}W$	$\frac{1}{24}\frac{WL^2}{EI}$	$\frac{5}{384}\frac{WL^3}{EI}$
(E)	$\frac{1}{8}WL$	—	—	$\frac{1}{192}\frac{WL^3}{EI}$
(F)	$\frac{1}{12}WL$ or $\frac{1}{12}wL^2$	—	—	$\frac{1}{384}\frac{WL^3}{EI}$

Table II. gives particulars of the values of shear, bending moment, slope and deflection for various methods of loading in beams and cantilevers.

§ 21. **Torsion.**—Torsion is the shear which is produced when one layer of a body is made to rotate on the next. Pure shearing stress is produced in a cross section of a cylindrical rod or shaft when it is twisted by applying equal and opposite couples to its ends, if the axis of the rod coincides with the axis of the couples.

The torsional shear stress varies in intensity from a maximum at the outer layer to zero at the axis, provided Hooke's Law holds, and under the same conditions torsional strain is proportional to the distance from the centre of the shaft.

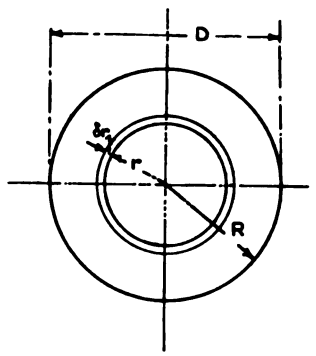


FIG. 18.

§ 22. **Relation between Twisting Moment and Torsional Stress.**—The external torque or twisting moment = the moment of resistance of the section. Consider a section of a shaft (Fig. 18) whose radius is R and diameter D subjected to an external torque T.

Take an elementary ring in the section whose distance from the axis of the shaft is r and breadth δr.

If f_r is the intensity of shear stress at distance r from the axis and f_s is the intensity of shearstress at the outside surface, radiusR.

$$\frac{f_r}{f_s} = \frac{r}{R} \text{ or } f_r = \frac{r}{R} f_s.$$

The total shear stress of the elementary ring

$$= f_r \times \text{area of the elementary ring}$$
$$= 2\pi r \times \delta r \times f_r$$
$$= 2\pi r \times \delta r \times f_s \frac{r}{R}$$

and the moment of stress $= 2\pi r . \delta r . f_s \frac{r}{R} r$. equation (1)

T = total moment of resistance of the section to torsion

$$= \frac{2\pi f_s}{R} \int_0^R r^3 dr . = \frac{2\pi f_s}{R} \times \frac{R^4}{4} = \frac{\pi}{16} f_s D^3.$$

For a hollow shaft having an internal radius $= R_1 = D_1/2$
and an external radius $= R = D/2$

$$T = \frac{2\pi f_s}{R} \int_{R_1}^R r^3 dr . = \frac{2\pi f_s}{R} \left(\frac{R^4}{4} - \frac{R_1^4}{4} \right) = \frac{\pi}{16} f_s \left(\frac{D^4 - D_1^4}{D} \right)$$

From equation (1).

Moment of stress = $2\pi r dr f_s \frac{r^2}{R}$ = (area)$r^2 \frac{f_s}{R}$.

Therefore T (external torque) = the total moment of resistance of the section to torsion,

$$= \int(\text{area})r^2\frac{f_s}{R}$$

$$= \text{polar moment of inertia of the section} \times \frac{f_s}{R}$$

$$= f_s\frac{I_p}{R} = f_s Z_p$$

where Z_p = the modulus of the section in torsion.

I, the moment of inertia about an axis (polar moment of inertia), of a shaft has twice the value of the moment of inertia about a diameter.

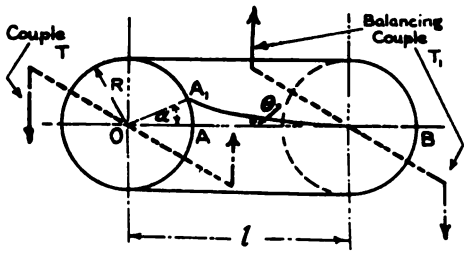


FIG. 19.

§ 23. **Relation between Twisting Moment and Angle of Twist.**—AB (Fig. 19) is a straight line drawn parallel to the axis on the surface of a shaft of radius R and length l.

If a couple T is applied to the shaft, and it is assumed that end B does not move, then the line AB becomes a helix and point A moves to A_1.

Let α = the angle in radians through which the shaft has been twisted or the angle of torsion,

then $\alpha = AOA_1 = AA_1/R$ or $AA_1 = R\alpha$.

The shear strain (θ) = the angle A_1B makes with AB (see § 10).

If the curved surface of the cylinder were developed into a plane one the curved line A_1B would be straight and the angle A_1BA therefore constant.

As the elastic strain is comparatively very small

$$\theta = AA_1/AB = R\alpha/AB = R\alpha/l \quad \text{equation (1)}$$

By Hooke's Law – shear stress = constant × shear strain (see § 10),

or $$f_s = C \times \theta$$

i.e. $$\theta = f_s/C \quad . \quad . \quad . \quad \text{equation (2)}$$

From equations (1) and (2) we get

$$\frac{f_s}{C} = \frac{Ra}{l}$$

or the angle of twist $$(a) = \frac{f_s l}{CR}$$

but $$f_s = \frac{T}{Z_p} \text{ (§ 22)}$$

therefore we have

$$a = \frac{f_s l}{CR} = \frac{Tl}{Z_p CR}.$$

$Z_p CR$ (or $T_p C$) is called the torsional rigidity of the shaft.

For a solid circular shaft of diameter = D

$$Z_p = \frac{\pi D^3}{16}$$

therefore $$a = \frac{16}{\pi D^3} \times \frac{2Tl}{DC} = \frac{32Tl}{\pi D^4 C}.$$

For a hollow shaft whose internal diameter = D_1
and external diameter = D

$$a = \frac{32DTl}{\pi(D^4 - D_1^4)C}.$$

Measurement of the strains within the limit of proportionality, during the torsion test, offer the easiest means for determining the modulus of rigidity (C).

CHAPTER III.

PROPERTIES OF MATERIALS.

§ 24. THERE is a great difference in the behaviour of materials when under load. They can roughly be divided into two classes :—

(i) *Ductile materials*, such as copper, gold, silver, mild steel, etc., which are capable of being extended by drawing or rolling without actual separation of their parts.

(ii) *Non-ductile or brittle materials*, such as cast iron, cast zinc, stone, concrete, etc., which have only slight plasticity, if any, and fracture without any considerable permanent deformation.

§ 25. **Load-extension or Stress-strain Diagrams.**—If we have a cylindrical bar of material of uniform diameter, which is held at one end and loaded with gradually increasing weights at the other, the increase in the length of the bar between two well-defined points a known distance apart can be accurately measured at various values of the load.

From the gauged length on the bar and the measured extensions the values of the strains can be calculated, while to every value of the strain there will be a corresponding value of the intensity of stress.

The extensions can be plotted as abscissæ and the loads as ordinates. The resulting curve gives an indication of the relation between load and extension for the material and is called a load-extension curve.

As an alternative the strains can be plotted against the corresponding intensities of stress giving a stress-strain diagram. Intensities of stress generally used are nominal ones calculated from the original diameter of the bar.

§ 26. **Curves for Perfectly Elastic and Perfectly Plastic Materials.**—In Fig. 20 deformations in compressions are plotted as negative extensions and compressive loads as negative tensile loads. The straight continuous line COT represents the load-extension diagram for a perfectly elastic material where the stress

is proportional to the strain. Deviation from this line indicates the presence of some plasticity.

For perfect plasticity the stress under which the material flows is constant. The load-extension diagram for a perfectly plastic material is therefore given by the line AB. OA represents the load at which plastic flow starts. As the material stretches the cross sectional area decreases and the load for constant stress is less.

From similar reasoning DE represents the load-deformation curve in compression for a perfectly plastic material.

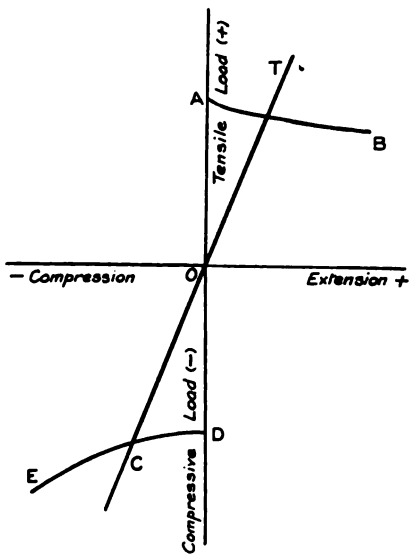


FIG. 20.

If L = the length of the test-piece and A = the cross sectional area under a load P, and L_1 = length of the test-piece and A_1 = the cross sectional area under a load P_1, and we assume that the volume remains constant.

Then $$AL = A_1L_1 \text{ or } A_1 = \frac{AL}{L_1}$$

under load P the stress intensity = P/A

and under load P_1 the stress intensity = $P_1/A_1 = \frac{P_1L_1}{AL}$.

For a perfectly plastic material the stress is constant

and therefore $$\frac{P}{A} = \frac{P_1 L_1}{AL} \text{ or } P_1 = P\frac{L}{L_1}.$$

Hence for a perfectly plastic material the load-deformation curves (AB and DE) are hyperbolic.

§ 27. **Load-extension Curves in Tension.**—(i) **Ductile Materials.**—A typical load-extension curve for a ductile material, such as mild steel, is given in Fig. 21.

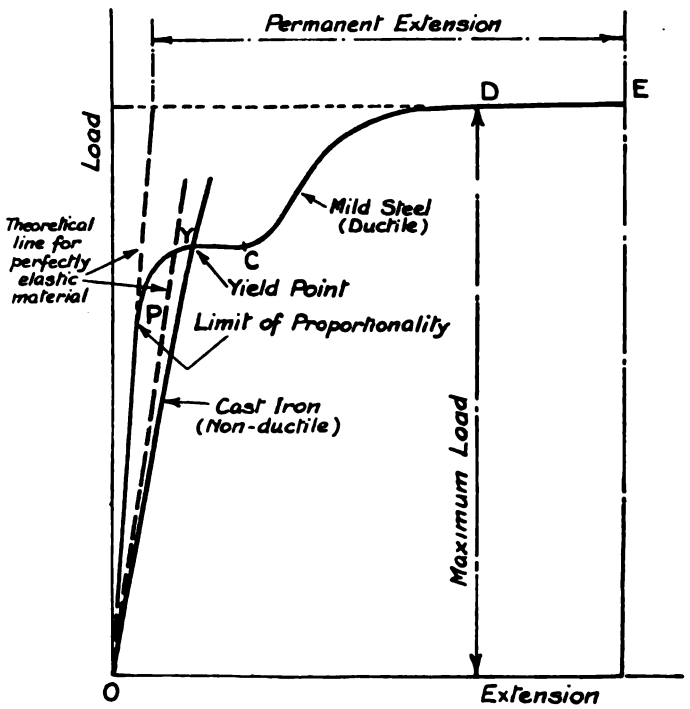


FIG. 21.—Load-extension curves.

There are several fairly well defined points in the curve for mild steel:—

(*a*) From O to P the material behaves elastically, load is proportional to extension and the line is straight. From this part of the curve the elastic modulus can be calculated.

(*b*) After passing P, there is a distinct variation from Hooke's Law, the extensions increase faster than the loads and there is a permanent set. Point P is called the limit of proportionality.

(*c*) At Y the material yields suddenly. There is a marked extension to C without increase of load and the material behaves plastically.

(*d*) After passing C the bar withstands a greater load and the behaviour becomes partly elastic and partly plastic. During this stage the material creeps, that is to say, if there is a pause in the steady increase of the load the extension is found to increase without increase of load. The curve from C to D is found by Dr. T. E. Stanton[1] to follow an approximately logarithmic law.

(*e*) A point D is reached at which the load is a maximum and the material again behaves like a perfectly plastic body.

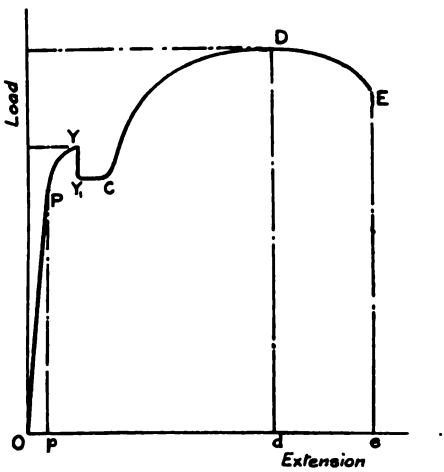


FIG. 22.—Load-extension curve for mild steel obtained by an autographic apparatus.

The bar extends very rapidly, due to local drawing out, and finally separates at E.

If the load-extension diagram is obtained by an autographic apparatus in which the actual load on the bar is measured as the material is stretched at a uniform rate, the diagram is found to take a slightly different form at one or two points, as is shown in Fig. 22:—

(1) At the yield point (Y) there is an actual reduction in the load and the curve drops to Y_1. This reduction is found, for mild steel, by Prof. Kennedy to be about 16 per cent. of the load at the yield point, Prof. Dalby obtains 13 per cent., while Robertson and Cook[2], who adopt a special arrangement to

overcome the inertia of the elastic system present in the apparatuses used by Kennedy [3] and Dalby [4], obtained a reduction of 27 per cent. as an average of twelve tests. They further confirm this result by tests in torsion.

Kennedy and Dalby find the part of the curve from Y_1 to C to be wavy. It is probable, however, that this irregularity is due to the inertia of the elastic system employed to which reference has just been made.

(2) After reaching the point of maximum load D, where the necking of the material commences, the curve slopes back, indicating a reduction of the load, and the piece finally breaks at E at a

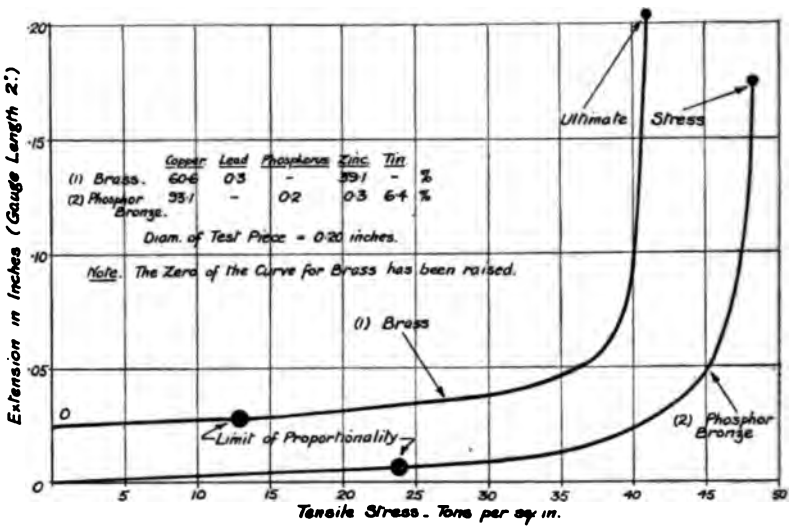


FIG. 23.—Load-extension curves for brass and phosphor bronze rod.

load much less than the maximum load. The actual intensity of stress at the breaking point E is, however, greater than that at D if the reduced area of the bar at E is considered in calculating the intensity.

The definite drop of load at the yield point in the autographic curve is characteristic of irons and low carbon steels in their normal state.

With some of the other ductile materials, such as high carbon steels, copper, brass, phosphor bronze, etc., the curve is smooth from start to finish. There is usually a proportional limit but no yield point. Examples of load-extension curves for brass and phosphor bronze are given in Fig. 23.

(ii) **Non-ductile Materials.**—A load-extension curve plotted from results obtained during a tensile test on cast iron is given in Fig. 24. The total extension is small when compared to that obtained from a ductile material and the test-piece breaks short without producing a " waist ".

It is seen that no part of the curve is straight and there is,

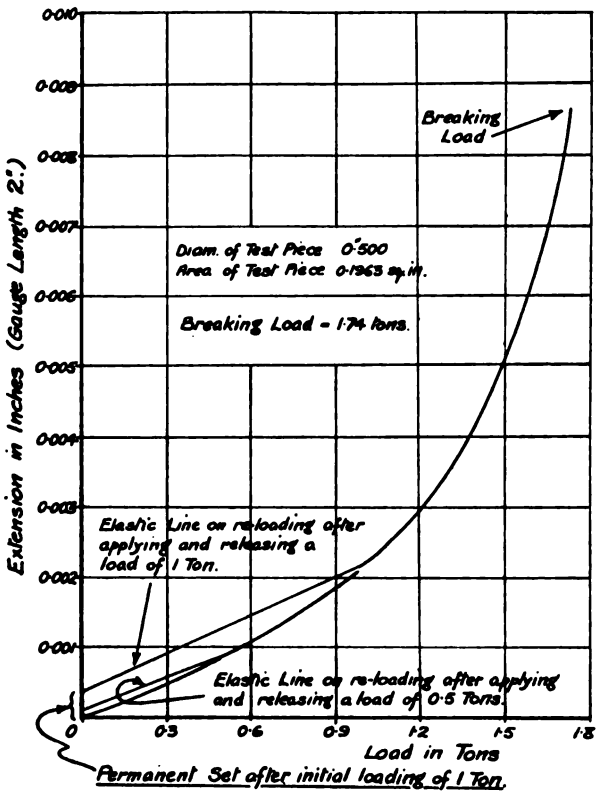


FIG. 24.—Tensile load-extension curve for cast iron.

therefore, no limit of proportionality. The material takes small permanent sets even at low loads and finally breaks without exhibiting any appreciable plasticity.

The modulus of elasticity of cast iron varies according to the part of the curve from which it is calculated, decreasing as the stress becomes higher. It is sometimes calculated from the working stress and the corresponding strain.

If the tensile test of a cast iron specimen is not carried to fracture a second loading will give a smaller permanent set than the initial loading.

§ 28. **Load-deformation Curves in Compression.—(i) Ductile Materials.**—Up to the limit of proportionality metals have approximately the same modulus of elasticity in compression as in tension. The initial slope of the load-deformation curve is, therefore, the same under both kinds of direct stress.

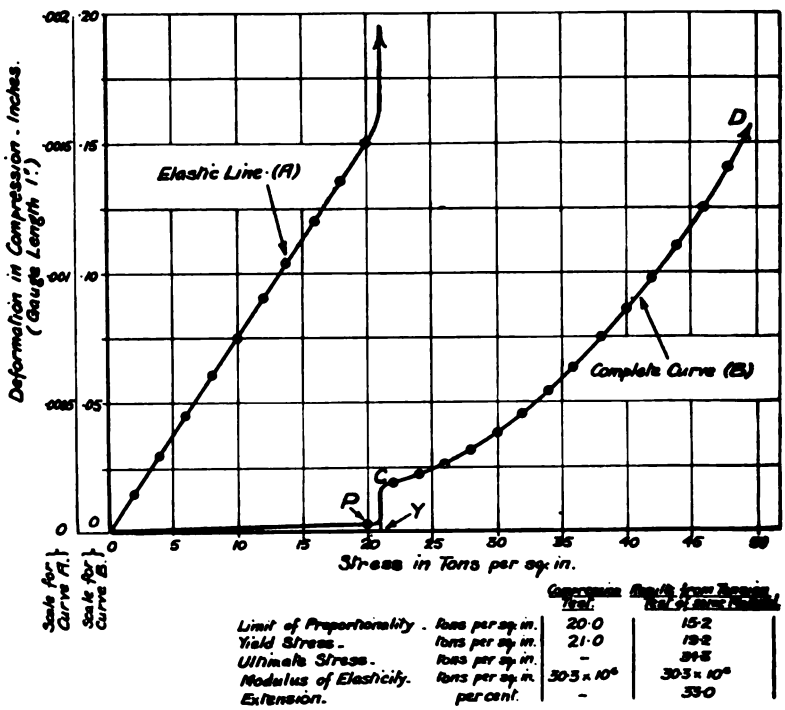

Deformation in Compression - Inches. (Gauge Length 1")
Elastic Line (A)
Complete Curve (B)
D
C
P
Y
Stress in Tons per sq. in.
Scale for Curve A.
Scale for Curve B.
Limit of Proportionality . tons per sq. in. 20·0 15·2
Yield Stress . tons per sq. in. 21·0 15·2
Ultimate Stress . tons per sq. in. - 31·5
Modulus of Elasticity. tons per sq. in. 30·5 x 10⁶ 30·3 x 10⁶
Extension. per cent. - 33·0

FIG. 25.—Stress-deformation curves for a ductile material tested in compression.

With mild steel there is also distinct yielding of the material at a load slightly higher than the load at the proportional limit.

After this point there is continual shortening of the test-piece accompanied by lateral expansion. The curve takes the form given in Fig. 25 where

P = limit of proportionality
Y = yield point
CD = plastic period.

For perfect plasticity the curve CD should be hyperbolic.

The curve CD continues almost without limit as there is no fracture of the material. Provided it is short enough to avoid buckling a cylindrical test-piece will shorten and bulge out into the form of a barrel.

For other plastic materials, such as copper, brass, aluminium, lead, etc., there is no yield point but the plastic period more closely follows theoretical plasticity.

Where the test-piece has a length which is more than four times the diameter there may be a tendency, owing to initial in-

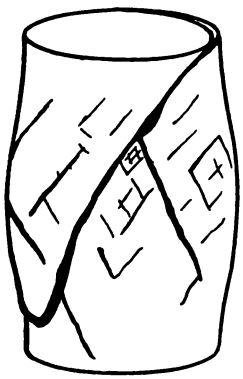


FIG. 26. — Compressive fracture of cast iron.

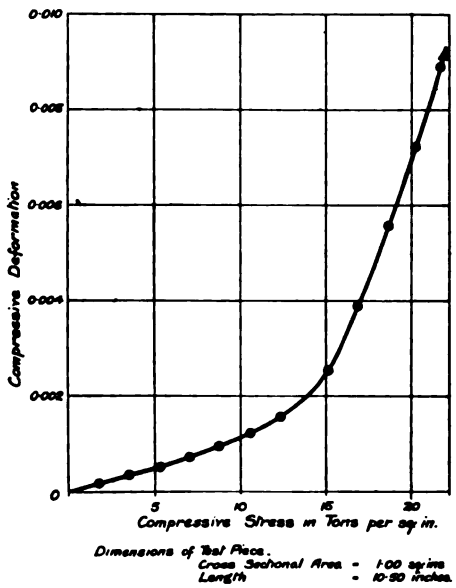


FIG. 27.—Compression test on a grey cast iron column.

equality in the distribution of stress, for it to bend. In practice struts or columns are usually so long that the principal cause of failure is the stress caused by bending.

(ii) **Non-ductile Materials.**—A brittle material, such as cast iron, fractures by shearing on inclined surfaces and the amount of deformation at the point of fracture is small. If the height of the test-piece is at least 50 per cent. greater than the width, the fracture may take the form of shear along a single surface, dividing the specimen into two pieces. The angle of this plane of rupture is about 35° from the axis of the applied load (i.e. 55° with the horizontal), see Fig. 26.

For shorter test-pieces shear takes places on more planes than one, splitting off the outside portions. The crushing stress is greater than if the height was sufficient to allow shear along a single plane.

A compressive load-deformation curve for cast iron is given in Fig. 27, from which it will be seen that it is of the same form as that for cast iron in tension.

§ 29. **Torsional Stress—Strain Diagrams.**—If, with a tor-

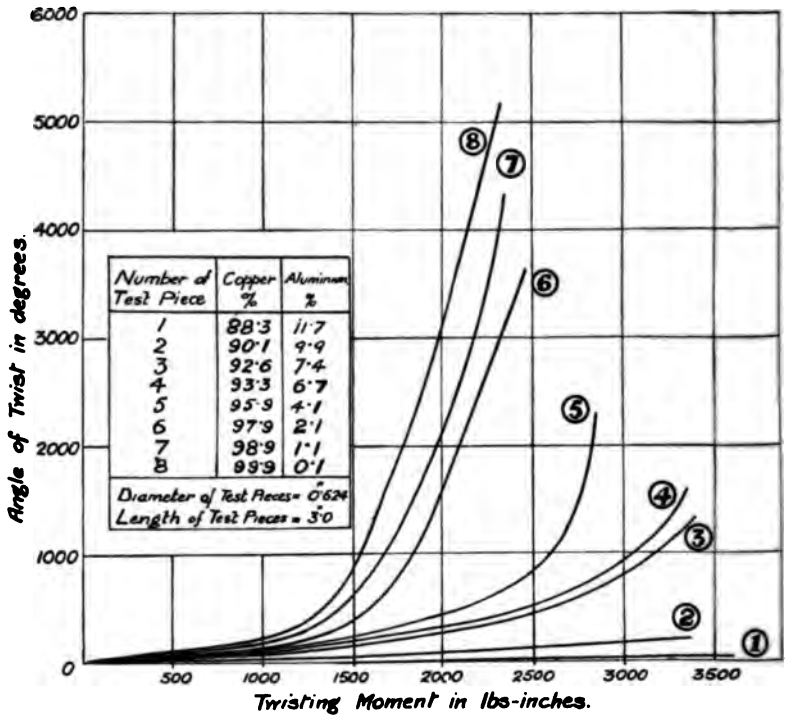


FIG. 28.—Torsion tests on copper aluminium alloys.

sion test, the external torques applied to the test-bar are plotted as ordinates and the corresponding amounts of twist of the bar as abscissæ, a curve is obtained of approximately the same form as the load-extension curve of the tension test.

When the dimensions of the test-bar are known the modulus of rigidity can be calculated from the slope of the early part of the curve. The intensity of shear stress, while the material behaves elastically, is proportional to the distance from the axis of

the bar, being therefore a maximum at the outside, but after the limit of proportionality is reached the distribution of stress across the section varies.

Curves connecting twisting moment and angle of twist for various copper aluminium alloys are given in Fig. 28.

§ 30. **Work Done in Producing Strain.**—A load can be applied to a test-bar in three ways :—

(i) Gradually.

(ii) Suddenly, but without impact or shock.

(iii) Suddenly with impact.

The work done by the load must be taken up by the bar.

(i) *Gradually Applied Load.*—This is the condition appertaining to the ordinary tensile test. If OT (Fig. 29) represents the portion of the load - extension curve within the limit of proportionality (which is assumed to be at T), the work done during any instant is equal to the product of the extension during that instant, say *mn*, and the load *mr*. The period can be considered to be so short that the load is constant throughout.

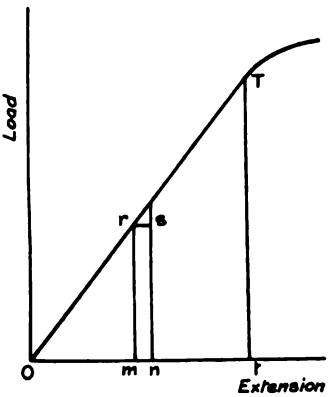


FIG. 29.

Let x = the extension at the limit of proportionality = ot

P = the load at the limit of proportionality = tT

A = cross sectional area of the bar

L = the initial length of the bar

s = the intensity of stress at the limit of proportionality = P/A.

As the load gradually increases from O to P and the extension increases proportionally from O to x, the work done by the load is represented by the area of the triangle otT. The work done is therefore equal to $\frac{1}{2}Px$ (i.e. the average load multiplied by x).

According to Hooke's Law, stress = E multiplied by strain

therefore $$\frac{P}{A} = E\frac{x}{L} \text{ or } x = \frac{PL}{AE}$$

and the **resilience,** which is the work done in stretching the bar up to the limit of proportionality,

$$= \tfrac{1}{2}Px = \tfrac{1}{2}P \cdot \frac{PL}{AE} = \frac{\tfrac{1}{2}P^2L}{AE} = AL \cdot \frac{s^2}{2E}$$

$$= \frac{s^2}{2E} \times \text{volume of the bar}$$

$\frac{s^2}{2E}$ is the resilience per unit volume.

It follows, therefore, that the total work done in breaking the bar is equal to the area below the load-extension curve. Thus we see (referring to Fig. 22, § 27) that this work consists of three parts :—

(*a*) The elastic work or resilience = area O*p*P.
(*b*) Work partly elastic and partly plastic = area *p*PYY_1*c*D*d*.
(*c*) Nearly perfectly plastic work (during local extension) = area DE*ed*.

For cast iron and non-ductile materials (*c*) = O, while for mild steels and ductile materials (*a*) is comparatively small.

(ii) *Load Applied Suddenly but without Shock* (*within the Limit of Proportionality*).—A scale pan is hung from a test-bar whose cross sectional area = A and a weight W is put on to the scale pan but independently supported so that no load is applied to the bar. Should the support be quickly removed the weight W is applied to the bar suddenly but without shock or impact. W is carried through the whole of the extension of the bar. If x is this momentary extension then the work done by the weight = Wx.

If s = the momentary intensity of stress in the bar whose cross sectional area is A, s increases from O to a maximum and the work done on the bar = $\frac{1}{2}sAx$. The work done by the weight and the work absorbed by the bar must be equal—

therefore $$Wx = \tfrac{1}{2}sAx \text{ or } s = \frac{2W}{A}.$$

That is to say, the intensity of stress and therefore the strain under these conditions of loading is twice that obtained under gradual loading.

(iii) *Load Applied Suddenly with Impact* (*within the Limit of Proportionality*).—If the weight W is dropped on to the scale pan from a height h, there is kinetic energy in the falling weight (= Wh) which must be absorbed by the test-piece.

If x is the momentary extension, the total work done by the weight = W(h + x).

If s (as before) = the momentary intensity of stress in the bar whose cross sectional area is A, then the work absorbed by the bar = $\frac{1}{2}sAx$

and $$W(h + x) = \tfrac{1}{2}sAx$$

Now $x = sl/E$, where l = length of the bar

$x = el$ and $s = Ee$, where e = the strain

therefore $$W(h + x) = \tfrac{1}{2}sAx$$

$$= \tfrac{1}{2}sA \cdot \frac{sl}{E}$$

$$= Al \times \frac{s^2}{2E}$$

and where x is small in comparison to h

$$s = \sqrt{\frac{2EWh}{\text{volume of the bar}}}.$$

REFERENCES FOR CHAPTER III.

[1] Stanton, "Memoirs Manchester Lit. and Phil. Soc." Vol. VIII., Series 4, 1894.

[2] Robertson and Cook, "The Transition from Elastic to the Plastic State in Mild Steel," "Roy. Soc., Proc.," Vol. 88, 1913, pp. 462-471.

[3] Kennedy, "Inst. Mech. Eng., Proc.," 1886.

[4] Dalby, "Roy. Soc., Proc.," Vol. 86, p. 414.

CHAPTER IV.

TESTING MACHINES.

§ 31. **General Methods.**—There are certain methods of test which are applicable to all branches of test work. The complexity of the machines employed for these tests depends upon the number of purposes for which it is intended to use them. This complexity is dependent upon

(1) The variety of materials it is required to test.
(2) The kinds of straining action needed.
(3) The form and size of specimen to be tested.
(4) The magnitude of the forces to be exerted and measured.
(5) The accuracy required in the results.

By limiting the requirements, the testing apparatus can be made of great simplicity. For instance, in a transverse testing machine such as is used for checking the quality of cast iron in a foundry, the test-pieces can all be of one size, the straining action is always the same (the test-piece being broken as a beam), the amount of strain is comparatively small and there is not a great deal of variation of the breaking load. A machine such as this is simple and effective.

Every increase in the requirements adds additional apparatus to the machine. An accessory for one purpose will often interfere with the running of the machine for another purpose, thus causing loss of time in making the necessary adjustments for the experiments in hand, involving great care in the setting of the machine and making it more difficult to handle. It is therefore in the interest of the user to carefully consider the functions which the machine will be called upon to perform and to limit them to a minimum. In this way increased efficiency is obtained with minimum cost.

The simplest method of testing is by direct loading and the earlier researches on strength of materials were carried out by this method. Galileo (1638) and Muschenbrock (1729) made many tests on a small scale by this means, and where it can still be applied it is the simplest and best method of testing available.

Owing to the difficulty of handling heavy loads it is only suitable for use with weak materials.

When, at the beginning of the nineteenth century, the demand came for tests on a larger scale, it was necessary to consider other means of applying the force than by direct loading and, within a few years, the three arrangements found in modern testing machines were employed, viz.:—

(*a*) Load applied by hydraulic press—no weighing device but load calculated from the pressure on the ram.

(*b*) Load applied by gearing at one end—weighing lever at the other end.

(*c*) Load applied by hydraulic press at one end—weighing lever at the other end.

In 1813 method (*a*) was employed by Brunton & Co. for a chain-cable testing machine. The arrangement for arriving at the load was not capable of giving very great accuracy. It was necessary to make an allowance to the load, which was deduced from the indication of a pressure gauge, for the friction of the packing of the ram or the cup leather, and the amouut of this friction was extremely variable.

The Whitworth hydraulic testing machine[1] and the 600-ton testing machine of the Union Bridge Company at Athens, Pa., U.S.A., both use the same principle. The 5000-ton Olsen[2] compression machine of the Geological Survey and the Bureau of Standards, and the 600-ton Olsen compression tester of the Rensselaer[3] Institute at Troy both record the load by the pressure in the hydraulic press, but with these machines the pressure is transmitted to a diaphragm whose area is smaller than that of the main ram. The pressure on the diaphragm is measured by a system of levers. Method (*a*) has been applied to modern testing machines by eliminating the packing and having an accurately fitted ram and cylinder with small clearance. By using oil the slight leakage between the ram and cylinder reduces the friction to a practically negligible quantity.

The evolution of the other two testing machine arrangements (*b* and *c*) from the direct loading method was due to the introduction of the lever. By placing a lever in between the test-piece and the dead load, the amount of weight required was reduced by the ratio of the lever arms. This arrangement, although quite suitable for small pieces possessing little ductility, was found to be open to the objection that, as the material stretched, the position of the lever could not be adjusted.

In 1817 Captain Brown constructed a cable testing machine

in which the deformation of the cable was neutralised, and the load applied, by means of gearing at one end, while the load was measured by a lever at the other.

The use of gearing was the method of straining used in America on machines of the lever type. The same arrangement, although common on small machines worked by hand in this country, had not, however, been used on power-driven machines until recently.

Another method of counteracting the deformation of the test-piece was applied by Lagerjhelm, of the School of Mines at Stockholm, who conducted experiments in 1825 on a 7-ton machine in which a hydraulic ram neutralised the deformation of the test-piece and applied the load, which was measured by weights acting on a knee lever. About the same time, that principle was also employed by Bramah[4] in the construction of a machine used at Woolwich Dockyard by the late Prof. Barlow for some of his experiments on the strength of materials. This method of construction is, however, always associated with the name of David Kirkaldy, who in 1866 erected, in London, his well-known machine of 400 tons capacity. The combination of hydraulic ram and levers has since been in common use in machines of many designs, the chief difference in these designs being in the arrangement of the lever or levers and their position relatively to that of the test-piece.

Thomasset,[5] in about the year 1872, measured the load on the lever by means of a diaphragm piston with an extremely limited motion, and balanced the load on the piston by a mercury gauge. Maillard and Emery a few years later dispensed with the lever and transmitted the whole load to the diaphragm. Emery[6] constructed a machine of 450 tons capacity in which the pressure on the diaphragm piston was measured by transmitting it to a smaller one in which the mercury gauge of Thomasset was replaced by a system of levers and weights.

The first essential requirement of a testing machine is accuracy, the load shown by the machine should be an accurate indication of the real load to which the test-piece is subjected. In order to obtain complete accuracy it is necessary that:—

(1) Simple means should be available for establishing the truth of the indications of the machine—it should be capable of being easily calibrated. This calibration may alter with use; if of the lever type the knife edges may wear or be displaced, and, on a three-inch fulcrum distance, one per cent. error in the readings would be caused by a displacement of only 0·03 inch.

(2) The sensitiveness in working should be adequate, i.e. small differences in the load should be readily indicated.

Another desirable feature is simplicity—not simplicity resulting from a mere reduction of the attachments for the various tests but that obtained by ensuring that the varied requirements are carried out without undue complications. This not only reduces the parts liable to alteration with use but renders the machine capable of rapid and easy manipulation during tests, a feature which is especially important in a machine to be used for commercial testing. Other requirements necessary in a machine for commercial testing are :—

(*a*) The tests should be accessible from the front of the machine and the scale and control levers within easy reach of the operator.

(*b*) The test-piece should be easily inserted in the machine, i.e. the method of gripping should be simple and convenient.

For laboratory work it is advisable that the machine should be conveniently arranged to take an autographic apparatus for registering the results and should be generally adaptable to all sorts of conditions which may from time to time be necessary for varied experimental work.

The liability of the testing machine to subject the specimen to momentary shocks should also be considered. The inertia in the lever and weights (in that type of machine) may increase the stress in the test-piece beyond that indicated by the scale reading of the jockey weight. The construction of each machine should therefore be understood by the operator, and in skilful hands errors due to this cause can be reduced to a very small amount.

§ 32. **Horizontal and Vertical Machines.**—Testing machines may be arranged in either of two ways :—

(i) Machines in which the load is applied horizontally—horizontal testing machines.

(ii) Machines in which the load is applied vertically—vertical testing machines.

For testing long specimens it is usual to employ a machine of the horizontal type in which it is necessary to support the test-piece and the grips which hold it, otherwise forces are applied to the test-piece which are not measured by the load measuring apparatus. The vertical testing machine, however, is more convenient to handle and, except in the circumstances mentioned above, is the arrangement generally adopted.

§ 33. **Modern Testing Machines.**—Modern testing machines usually consist of four main parts :—

(1) An arrangement for applying the load.

(2) An adjustment to neutralise the effect of the deformation of test-piece so as to provide that there is no movement of the point of attachment of the test-piece to the weighing apparatus.

(3) A method of measuring the applied load.

(4) Holders for connecting the test-piece to parts (1) and (3).

The various types of testing machine differ in the way in which these requirements are carried out. The first and second parts are usually combined and the load on the test-piece is applied to one end either by (1) a straining cylinder actuated by a pump and accumulator, screw compressor, or oil pump (hydraulic, rotary, or direct driven); (2) screw gearing driven by hand or by power (such as an electric motor). Screw power testing machines are divided into two general types—the rotary screw and the rotating nut.

The load or force exerted on the test-piece is measured—

(*a*) More commonly in Great Britain, by a lever or system of levers with weights or a movable counterpoise forming a weighing apparatus.

(*b*) By balancing it with fluid pressure acting on a diaphragm.

(*c*) By measuring the pressure of the oil or water in the straining cylinder.

(*d*) By calculating the load from the angle through which a weighted pendulum is lifted.

Testing machines using methods (*b*) and (*c*) have the advantage that they are cheaper to make than the weighing lever machine, are practically free from inertia forces, and the load is automatically adjusted to the stress. They, however, require very careful attention and calibration, and are considered by the Board of Trade to be undesirable for use when making acceptance tests.

§ 34. **Types of Testing Machines. — Lever Testing Machines.**—By far the largest number of machines measure the load by the use of a lever. The loading of the lever is effected either by (*a*) adding separate weights to a scale pan placed at a fixed leverage (i.e. fixed leverage and variable load); (*b*) having a single jockey which travels along the beam (i.e. fixed load and variable leverage); (*c*) a combination of (*a*) and (*b*).

These arrangements are indicated diagrammatically in Fig. 30. With either of the methods the following points must be borne in mind:—

(1) The lever during the test will change its position and, in order to secure constant leverage, the points of application of the

loads must be in a straight line, i.e. the centre of gravity of the moving weight and any knife edges employed must all lie in a straight line or, if the moving weight is hung from a knife edge, the knife edge must travel along that line.

(2) Any addition of weights during a test must be carried out without producing shocks on the specimen. In those machines in which weights are added to the scale pan it is usual to carry this out by a mechanical arrangement such as is shown in Fig. 31.

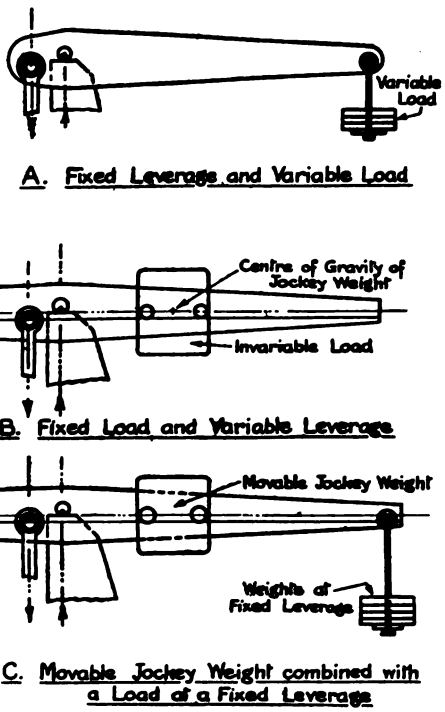

Variable Load
A. Fixed Leverage and Variable Load
Centre of Gravity of Jockey Weight
Invariable Load
B. Fixed Load and Variable Leverage
Movable Jockey Weight
Weights of Fixed Leverage
C. Movable Jockey Weight combined with a Load of a Fixed Leverage

FIG. 30.—Methods of applying the load in lever testing machines.

In some machines the load is measured by the height to which a pendulum bob is raised. This can be considered as a modification of the lever method. Fig. 32 shows how it was employed in the tests described in the British Engineering Standards Association Report, No. 55.

It is desirable that, on the same machine, the percentage accuracy of reading the load should be the same with small as with

large specimens, and it is therefore usual to arrange modern testing machines so that the same length of scale is equivalent to at least two values of the load. This is carried out either by varying the leverage or varying the weight of the moving poise.

The leverage is varied by providing alternative fulcra. This method is introduced into the Wicksteed vertical machine (Fig. 38) and consists in providing a third knife edge which can be

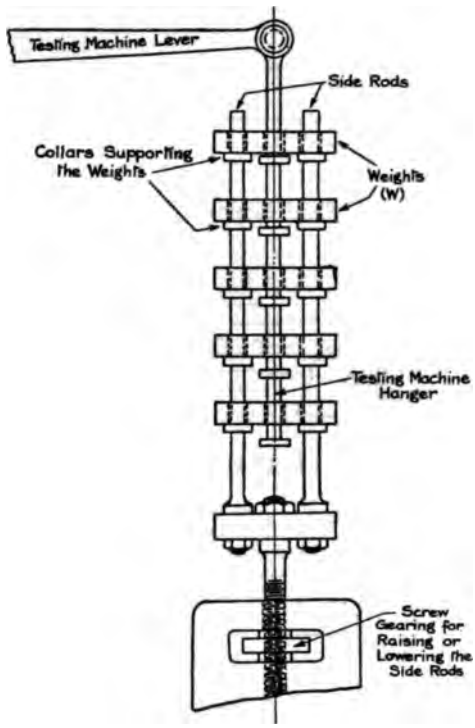


FIG. 31.—Mechanical arrangement for adding weights to testing machine lever.

put in or out of gear. When it is in place, the knife edge distance is large and the machine is arranged for use with weak specimens otherwise the full capacity of the machine is available. Thus the same counterpoise may represent say 50 or 100 tons, for the same travel of the counterpoise along the lever, according to which fulcrum is used. The method of operating the third knife edge is shown in Fig. 33. The three knife edges are in the same line but the movable support (Y) for the third knife edge

(Z) is raised so that when it is placed in position by the worm gear there is a slight clearance over the support (X) as shown in Fig. 33 *b*.

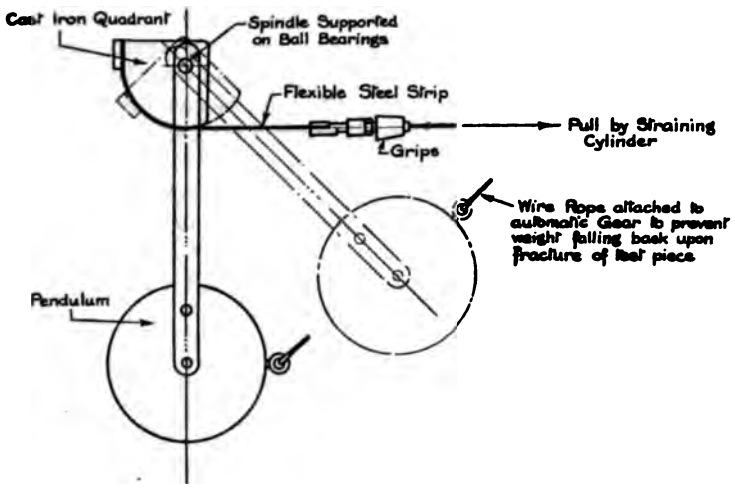

Cast Iron Quadrant
Spindle Supported on Ball Bearings
Flexible Steel Strip
Grips
Pull by Straining Cylinder
Wire Rope attached to automatic Gear to prevent weight falling back upon fracture of test piece
Pendulum

FIG. 32.—Diagram of weighted pendulum testing machine.

The weight of the moving poise is varied in machines supplied by Messrs. W. & T. Avery, Ltd. The counterpoise is split and

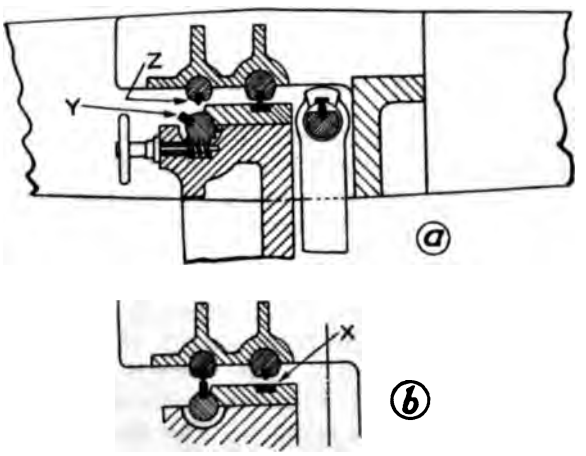


FIG. 33.—Wicksteed's alternative fulcra.

for small loads a part of it is detached and used as a separate poise.

In order to obtain a high mechanical advantage, without making the short arm of the lever very small, some machines use a multiple system of levers each with comparatively small mechanical advantage. It is therefore convenient to divide lever machines into two sections: (1) those using a single lever, (2) those in which the levers are compounded, and to subdivide those sections according as to whether the test-pieces are vertical or horizontal, and whether the load is applied by a straining cylinder or screw gearing.

§ 35. **Single Lever Machines (Vertical).**—(i) Fig. 34 shows diagrammatically the simplest arrangement of a single lever machine, this being the principle adopted by Mr. Wicksteed.[7] It is a vertical machine with a single horizontal lever (A) on top,

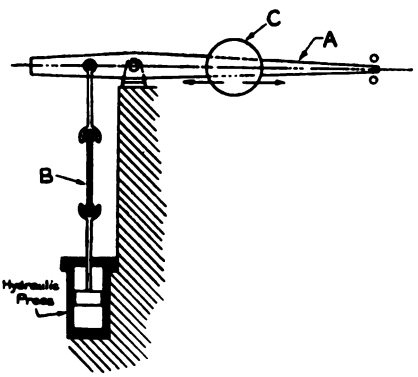


FIG. 34.—Single lever vertical testing machine.

to which one end of the test-piece (B) is connected. A movable poise (C) weighs the load which is applied to the other end of the test-piece by the ram of an hydraulic press (as shown) or by screw gearing. The following are modern examples of machines which use this principle:—

(ii) **"Avery" 10-ton Electrically Driven Single Lever Testing Machine.**—This machine is shown in Fig. 35. (A) is the weighing lever and (B) the poise weight of 840 lbs. which is moved by a control screw (C). The screw is driven by hand at (D) through gearing (E and F) and a Hooke's joint (G) which is placed on a line with the fulcrum. The straining of the test-piece is produced through worm and spur gearing by means of a variable speed electric motor (H), with a speed range of 4 to 1, whose control is located at (I) on the standard near to the hand wheel propelling the poise weight.

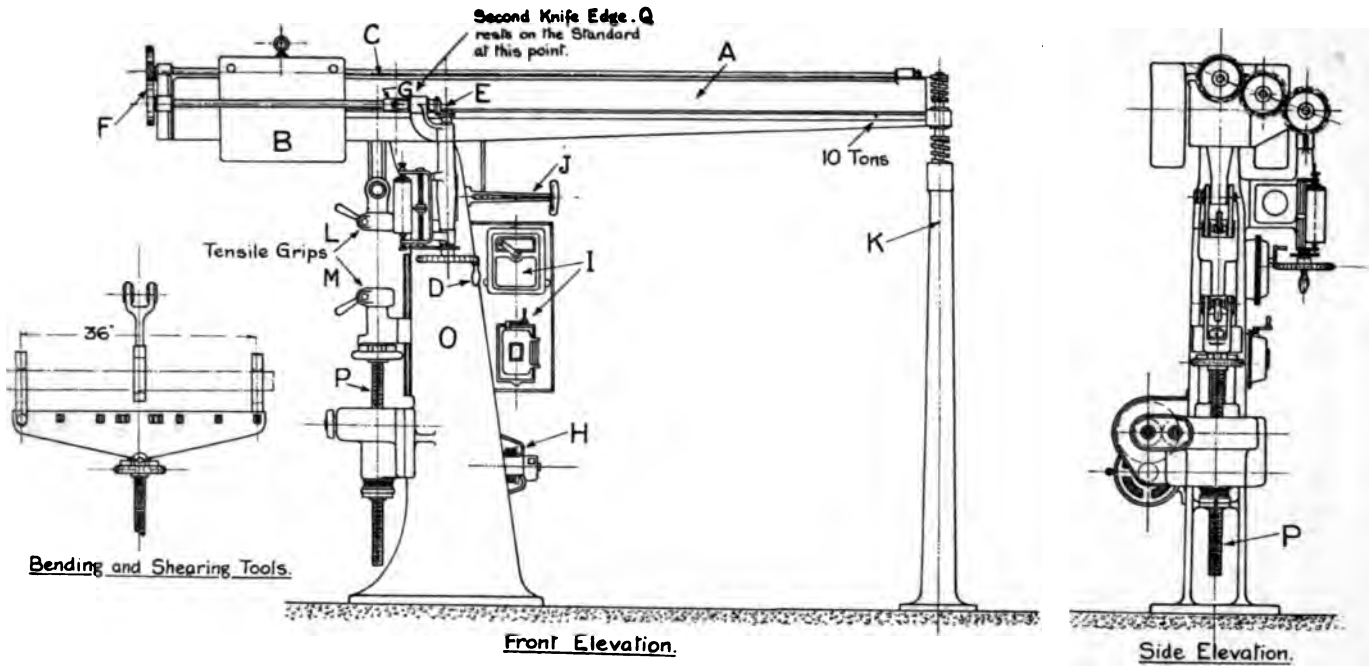


FIG. 35.—Avery's 10-ton electrically driven single lever testing machine.

The indicator (J) which shows the equilibrium of the steelyard is also close at hand so that the operator has all the controls within easy reach. The free end of the lever plays in a space in the supporting pillar (K). Springs are provided to take the shock when the test-piece breaks.

The grips for the test-piece are shown at L and M, these are provided with attachments for test-pieces with either screwed or enlarged ends (see Fig. 69, § 45). The upper grip is attached to the lever through a link and knife edge, while the lower one, which slides in guides in the standard (O), is connected to the straining screw (P). The second knife edge of the machine (Q) rests on the standard (O).

For prolonged tests, where the possibility of leakage in a hydraulic machine would be disadvantageous, an electrically driven machine such as this is sometimes preferred.

These machines are made by W. & T. Avery, Ltd., Birmingham, in various sizes up to 50-ton capacity. In the larger machines the supports are of heavier construction. The grip holders are situated between two columns bolted to the gear box which forms the base of the machine. The straining gear, a worm drive running in oil, is totally enclosed in this box and is provided with a suitable ball thrust bearing. The top of the columns are bridged by a casting which supports the main knife edge. This type of machine can be provided with attachments for compression tests and bending tests.

(iii) **Denison's 30-ton Universal Testing Machine.**—The standard 30-ton testing machine, of the single lever type, made by Samuel Denison & Son, Ltd., Leeds, has the load applied by a straining cylinder worked by the pressure from a patent hydraulic rotary oil pump. This pump has a variable delivery in either direction whilst being continuously driven in one direction only. The drive can either be by direct coupling to an electric motor or by belt from a countershaft. A similar pump is used for driving the standard jockey weight in either direction, the speed at which it travels can be varied by means of a conveniently placed lever.

The machine has the cross beam, upon which deflection compression and shear tests are made, permanently attached, so that any test can be instantly undertaken without the equilibrium of the steelyard being disturbed or time being occupied in changing the apparatus.

Tell-tale devices are supplied for indicating to the operator the movements of the various parts, and the machine includes all the features which are indispensable for accurate work.

FIG. 36.—100-ton Buckton vertical testing machine installed at the National Physical Laboratory.

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(iv) **National Physical Laboratory 100-ton Testing Machine.**—This machine was supplied by Joshua Buckton & Co., Ltd., Leeds, and is shown photographically in Fig. 36.

The load is applied by an hydraulic ram and cylinder which

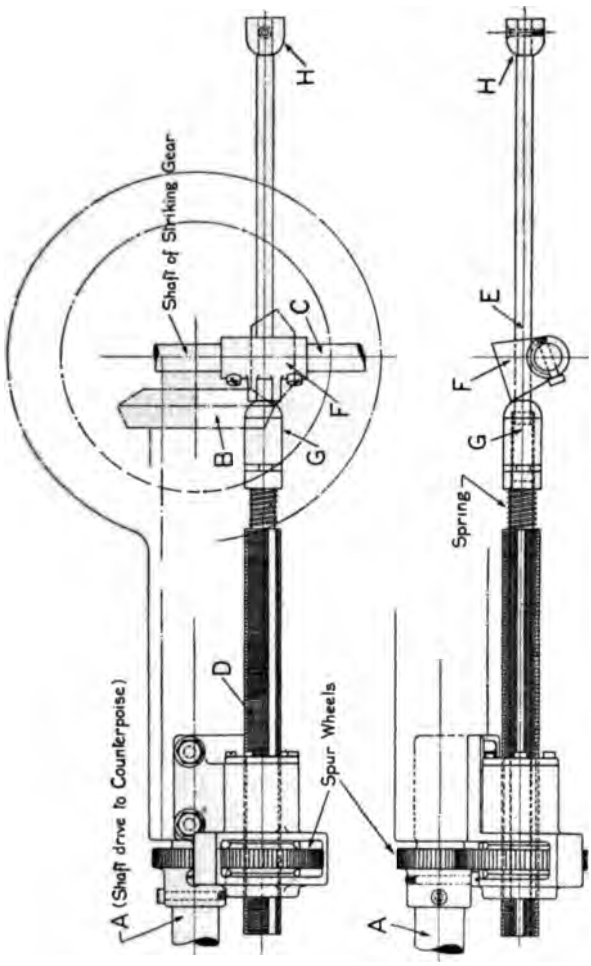

FIG. 37.—Variable automatic cut-off for Buckton 100-ton testing machine.

are placed in a pit below the floor level. A pressure of 1 ton per square inch is supplied to the cylinder by an hydraulic pump and accumulator driven by an electric motor. The counterpoise is driven by hand or mechanically by fast and loose pulleys operated from a suitable line of shafting. The machine seen in

the photograph is fitted with alternative fulcra (see § 34) giving a short knife-edge distance of either 3 or 6 inches, so that the jockey weight of 1 ton in travelling the full length of the scale can be arranged to give either a load of 100 or 50 tons.

Another feature of the machine is the arrangement which has been added at the National Physical Laboratory to prevent the jockey weight accidently running past the end of the scale in either direction. When a considerable number of tests have to be carried out, it is usual for the operator to measure the extension, contraction of area, etc., and enter up the results, while the counterpoise is running back for the next test. It detracts from his attention if he has to be continually on the alert to stop the counterpoise at the right time. The gear is shown in detail in Fig. 37 and operates on the belt throw-over gear. The shaft A operates the gearing for driving the weight along, placed at the end of the beam, and is worked from the small countershaft (not shown) through bevel wheels B. The striking gear of the countershaft is operated by a shaft C, which has a handle (not shown) on its lower end. A spur gear on shaft A operates a screw D through gearing. This screw is so arranged that it does not rotate but traverses horizontally as the weight is run along the beam. The screw carries a projection E working in a bracket F attached to the striking gear shaft C. Adjustable lugs G and H are fitted on to this projection and are arranged so that when the counterpoise reaches the extreme end of its travel, in either direction, one or other of the lugs G and H will rotate the striking gear shaft and throw the driving belt on to the loose pulley of the countershaft. The lugs can be adjusted so that, for any series of tests, the counterpoise will be stopped at any predetermined position along the beam.

A photograph of the gear is given in Fig. 38 from which the general arrangement of the apparatus relative to the other parts of the testing machine can be more easily seen. This photograph also shows the alternative fulcra referred to above.

(v) **Avery 2 and 10-ton Hydraulic Single Lever Machine.**—It is often convenient to use an hydraulic supply of low pressure. A machine designed by W. & T. Avery, Ltd., for a pressure of 45 lbs. per square inch is illustrated in Fig. 39, with the tensile test shackles in position.

The single lever has a counterpoise of 840 lbs. weight working on ball bearing rollers. This counterpoise is split into two poises of 168 and 672 lbs. weight respectively. The former

FIG. 38.—Automatic "throw over" gear on the National Physical Laboratory 100-ton testing machine. (The photograph also shows the alternative fulcra.)

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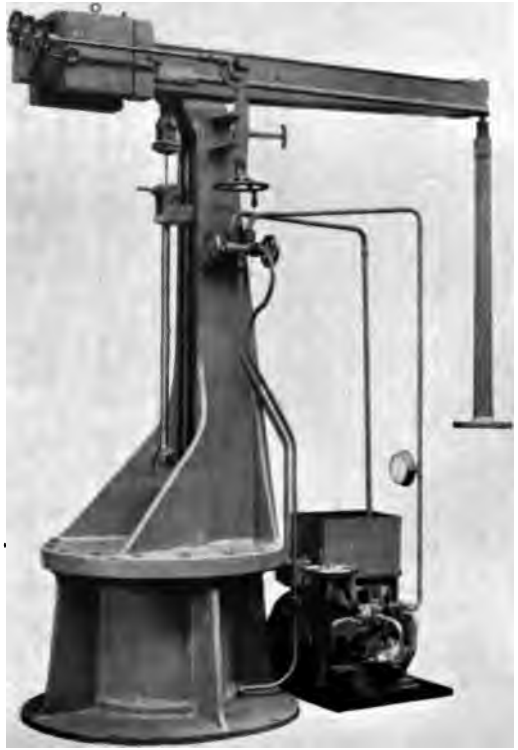

FIG. 39.

FIG. 40.

Hydraulic single lever testing machine for low pressure supply.

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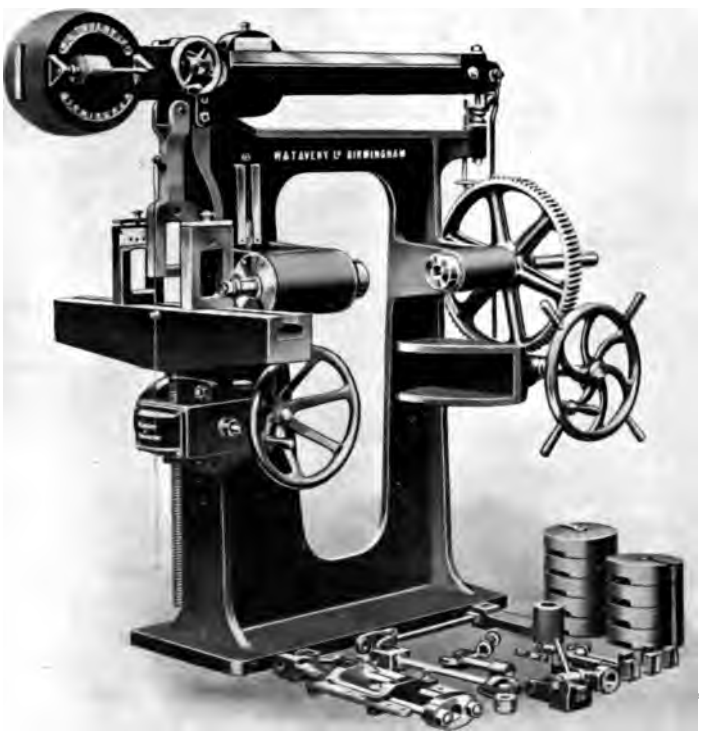

FIG. 41.—Small universal testing machine.

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poise (the smaller) can be used separately, and when this is done the range of the machine is from 0 to 2 tons and reads to 0·001 of a ton on the upper part of the scale. The complete counterpoise gives any load up to 10 tons, which is read to 0·01 tons on the lower part of the scale.

The column of the machine is made of extra length in order to test struts up to 5 feet long. The arrangement of the testing shackles for this purpose are shown in position in Fig. 40. The upper platen can be adjusted every 6 inches, on the rods connecting it to the ram rod, to allow for varying lengths of strut. The maximum travel of the ram is 15 inches.

A testing machine of this design forms part of the equipment of the National Physical Laboratory, where it is worked directly from the water mains at 45 lbs. per square inch and not through a Hele-Shaw pump as illustrated in Fig. 39.

A machine of this type is extremely useful for very accurate extensometer experiments but is rather slow in operation and requires either a platform or a comparatively costly pit for the cylinder and ram. This is principally due to the increased length for the strut tests.

(vi) **Small Universal Testing Machine (10,000 lbs.).**—For conditions where a power-driven machine is not required a hand-power machine, such as the one under notice, is sometimes found useful.

Machines of this or similar design are made by all the leading British testing machine manufacturers, the particular machine illustrated in Fig. 41 is of the Avery pattern.

The steelyard indicates loads up to 1000 lbs., by divisions of 10 lbs. (Vernier readings to 1 lb.), the remainder of the capacity being made up by means of nine loose weights. The poise is propelled entirely by gearing, no chain drive is employed.

The strain is applied by hand through a triple speed gear box, and screw, the tension specimen being held in grip wedges, in the usual manner. One movement of the handle opens and closes the grips.

The machine is shown fitted up ready for bending tests. For compression tests supplementary tools are inserted into the machine, the same being done for tension tests of metals, the testing of cement by tension and for detecting the hardness of steel, etc., on the "Brinell" principle.

Torsion tests, up to a maximum diameter of 0·875 inches, are carried out through the medium of worm gearing, the load being communicated to the steelyard through a small lever.

Readings obtained from the steelyard give a maximum twisting moment of 10,000 lbs. ins.

§ 36. **Single Lever Machines (Horizontal).—The Werder Testing Machine.**[8]—The Werder machine, extensively adopted in Germany, is a horizontal single lever testing machine, in which the load is applied by hydraulic pressure, but is measured by dead weights on a single lever. The type was originally designed by Ludwig Werder in 1852 and exhibited at the Munich Exhibition in 1854, since when a considerable number of similar machines have been constructed. The arrangement of the machine is illustrated diagrammatically in Fig. 42, from which it will be seen that (1) only one lever is required for a 500 to 1 leverage, and (2) by an ingenious arrangement, the ram, lever, and weights are all at one end of the machine. It is thus a simple matter to adapt the machine to take test-pieces of any length.

The test-piece T is held at one end in the framework of the machine A, and at the other pulled by the short arm L_1 of the

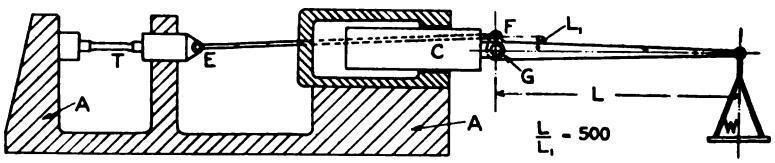

FIG. 42.—Arrangement of Werder testing machine shown diagrammatically.

lever, to which it is connected by a cross-head and long bolts shown in the diagram by a connecting rod EF. At the end of the long arm of the lever hangs a scale pan W. The central fulcrum of the lever G rests on the end of the ram C, so that, as the test-piece extends, the ram moves out, carrying the whole measuring apparatus with it. The arm L is kept horizontal by the help of a lever which is fixed to it.

In order to obtain the large leverage, the length of the short arm L_1 is made very small (only 3 mm.). It is clear that this length cannot be checked with sufficient accuracy, a controlling arrangement is therefore provided consisting of a knee lever, with one fulcrum at E and the other on the frame, with a ratio of ten to one. The knife edges of this lever can be accurately measured by ordinary means and to test the accuracy of the 500 to 1 ratio, a direct calibration can be made.

The ram C is 11·8 inches in diameter, and the knife edges have a pressure on them of about 7 tons per linear inch at full load (100 tons).

The pressure is obtained from two pumps worked by hand or power and placed at the side of the machine—a small one of 0·4 inches diameter, used for the full load, and a larger one, 1·2 inches diameter, for use up to a load of 20 tons.

Full details of a Werder testing machine are given in "Engineering," Vol. XXXV, June 8th, 1883, page 530.

§ 37. **Compound Lever Testing Machines.—Vertical Machines with Screw Power.**—This is the arrangement of machine which is largely used in America and is shown diagrammatically in Fig. 43. The straining mechanism is of two types—the rotating screw and the rotating nut.

With rotating screw machines, the pulling screws pass

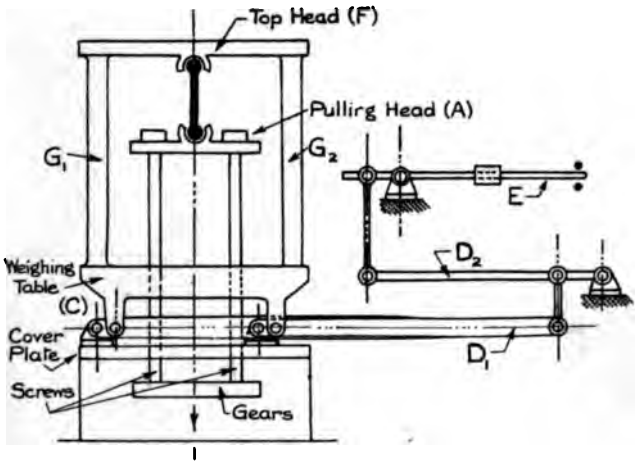

FIG. 43.—Diagrammatic arrangement of vertical compound lever testing machine (screw power).

through nuts which are fastened to the pulling head A. The screws are keyed to and rotate with the main gears through bearings in the cover plate, thus moving the head up and down.

In the rotating nut type of machine, bronze nuts are fastened in the main gears and rotate with them, pulling the screws, to which the head is attached, up and down. The gears rest on long pedestals bolted to the base plate of the machine and in these pedestals keys are fixed which prevent the screws from turning.

The thrust, in each case, is taken on the under side of the cover plate by ball or roller bearings. The rotating nut machine

usually requires a pit or opening in the foundation for the screws which project below the base line of the machine.

The weighing apparatus consists of a weighing table C, levers D_1 and D_2, and a graduated beam E. For tensile strain there is also a weighing or top head F and two or four weighing columns G_1 and G_2 attached to the weighing table.

This type of testing machine is often preferred because of the small amount of floor space required when compared to that occupied by a single lever machine of the same capacity.

Until recently they have been made almost exclusively in the United States of America and standard machines of various sizes with maximum capacities from 5 to 200 tons are supplied by

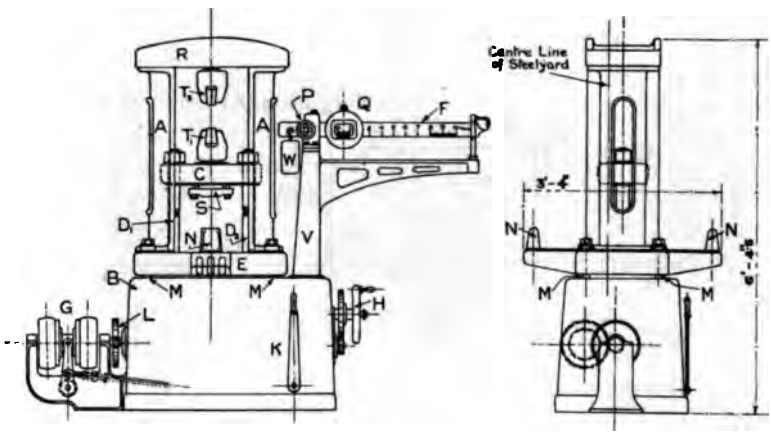

FIG. 44.—Avery's 10-ton compound lever vertical testing machine for testing in tension compression, bending and shearing.

Riehlé Bros. Testing Machine Co., and Tinius Olsen Testing Machine Co. of Philadelphia.

Avery's 10-ton Compound Lever Testing Machine.—This machine has been recently designed by W. & T. Avery, Ltd., and is arranged on the double screw rotating nut principle. It is shown in Fig. 44.

Straining Mechanism.—D_1, D_2 are the straining screws which are bolted to the cross-head of the machine (C). On the top of this cross-head one of the sets of grips (T_1) for tensile tests are attached, while to the underside there is a spherical seated platen (S) for compression tests.

The machine is equipped with power-driven straining gear worked by forward and reversing belts (G), through spur gearing

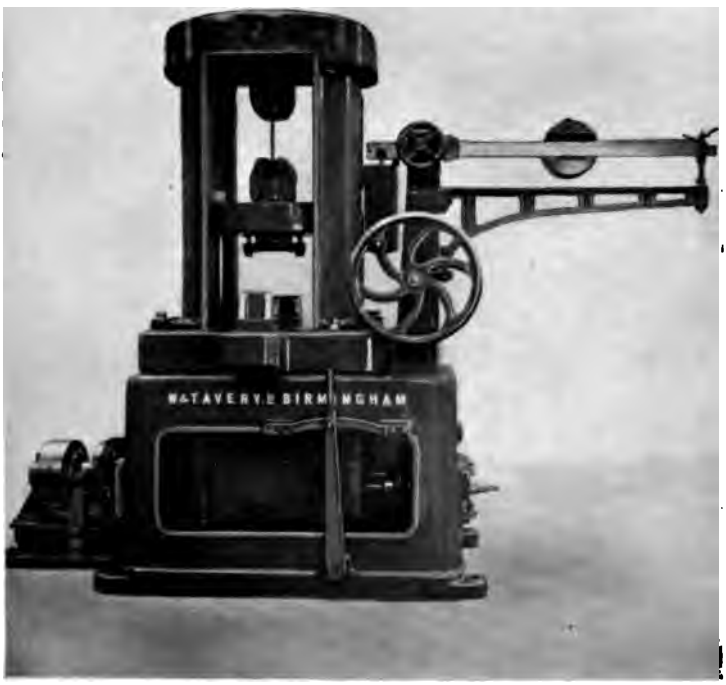

FIG. 45.—Vertical compound lever testing machine.

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(L) and worm gearing in the box (B) of the machine. The worm gearing rotates two driving nuts, one on each of the main screws D_1, D_2. Each screw is fitted with feathers, in longitudinal slots cut through the threads to prevent them from turning. Rotation of the nuts thus cause the screws to either rise or fall, carrying the cross-head (C) with them.

The thrust of the nuts against the top of the box (B) is taken by suitable thrust washers.

The belt drive is operated from a lever (K) while quick return of the cross-head may be obtained by means of a hand-wheel (H) at the end of the machine.

Weighing Mechanism.—The weighing mechanism is essentially the same as that of a platform weighing machine. The load on the test-piece, applied by the straining mechanism, is communicated to the platform (E) either directly in a compression test, or through the medium of the upper bridge (R) (to which the grips (T_2) are attached) and the columns (A) in the tensile tests.

The platform (E) rests, by means of four verges (M) fitted with hardened steel bearings, upon the hardened steel knife edges of the weighing levers. These latter are connected to the steelyard (F) by means of a mild steel connecting rod. The lever multiplying arrangement, which is of the Avery weighing machine pattern, is all contained in the box (B) of the machine.

The steelyard, which has its main knife edge on the framework (V), is graduated from zero to 10 tons by divisions of 0·1 ton, these latter being sub-divided, by a vernier upon the poise, to give readings down to 0·01 ton. The poise (Q) is propelled entirely through gearing by a hand-wheel (P)—no loose weights are required—and the balance of the steelyard is arranged by a weight (W).

The machine is provided with supports (N) for bending tests on spans of 12 inches, 24 inches and 36 inches. The maximum stretched length for tensile tests is 15 inches and compression pieces can be taken up to a length of 15 inches.

As this is a rotary nut machine, holes are required in the foundation for the screws to pass through.

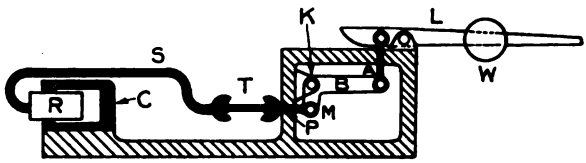
A photograph of the machine is given in Fig. 45. In this photograph the hand-wheel for applying the strain is placed on the steelyard framework and, for quick return of the cross-head, it is transferred to the shaft sticking out of the box (B) shown in Fig. 44.

§ 38. **Horizontal Compound Lever Machines.**—For testing long specimens a horizontal machine is essential. In order to obviate the difficulties introduced by the small knife-edge distance of the Werder machine, multiple lever arrangements are used. A bell crank lever is adopted to convert the horizontal force into a vertical one, and this is combined with the weighing lever, either with or without the introduction of intermediate levers.

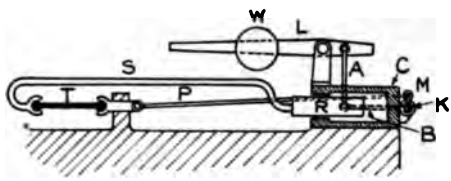
There are two principal arrangements of machines of this type :—

(*a*) Greenwood & Batley's horizontal testing machine and W. & T. Avery's horizontal testing machine.

(*b*) Buckton's horizontal testing machine.



(a) Greenwood and Batley Testing Machine



(b) Buckton Horizontal Testing Machine

FIG. 46.

The main difference in these designs is in the relative position of the cylinder and ram (R, Fig. 46) to that of the weighing lever (L). In machines of type (*a*) they are at opposite ends, whereas in type (*b*) they are both at the same end.

The ram (R) is connected to one end of the test-piece (T) by a frame and cross-head indicated in Fig. 46 by the rod (S). The other end of the test-piece connects to the lever (L) by means of—

(i) Bolts and cross-head (P) indicated in the Buckton machine by a connecting rod.

(ii) A bell crank lever (B) with its main knife edge at K.

(iii) A link (A).

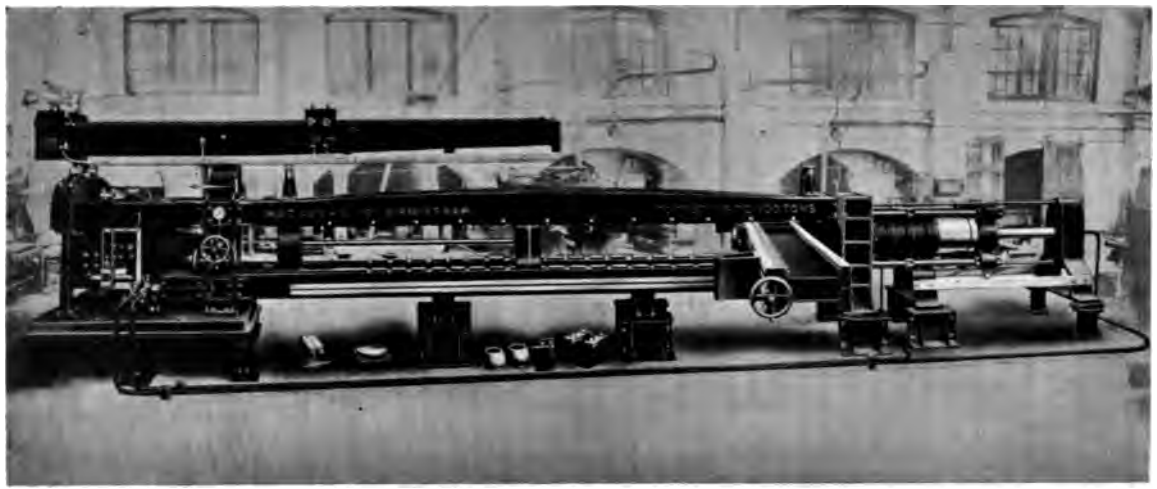


FIG. 47.—100-ton horizontal testing machine.

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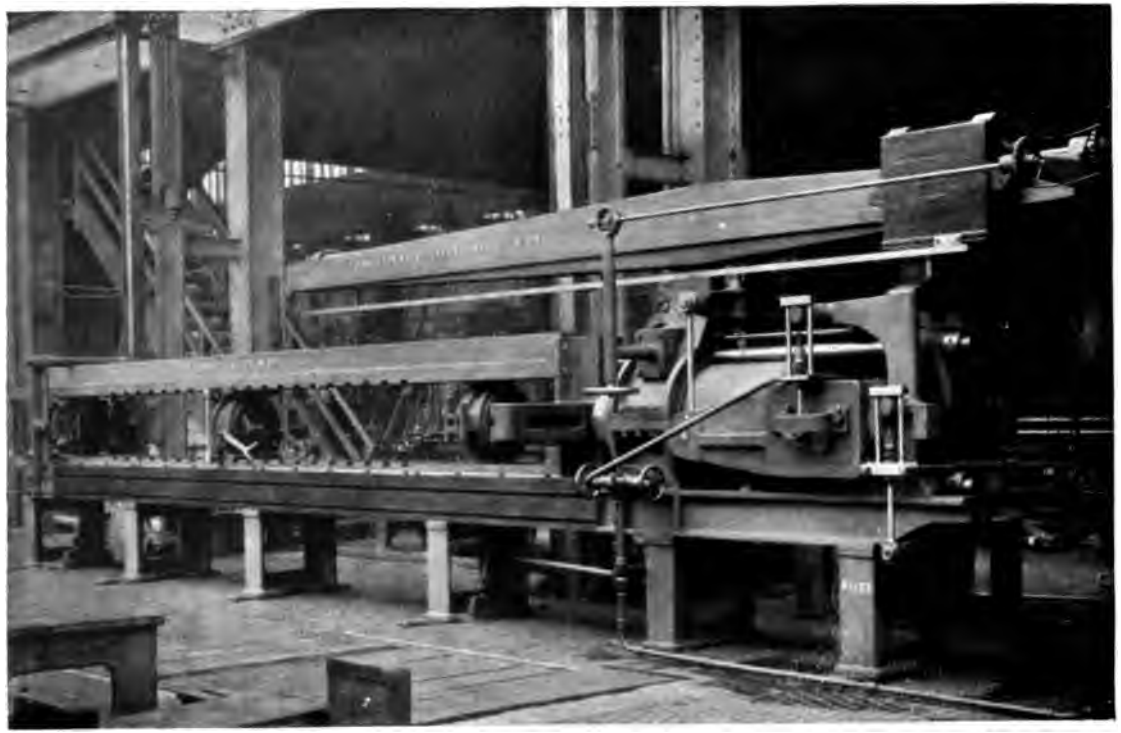

FIG. 48.—Buckton horizontal testing machine.

[*To face p.* 59.

100-ton Avery Horizontal Machine.—There are examples of a 50-ton Greenwood & Batley machine and a 100-ton Avery horizontal machine at King's College, London.

The Avery machine shown in Fig. 47 is erected at the Glasgow and West of Scotland Technical School. The arrangement is practically the same as that adopted for the 700,000-lb. machine at Birmingham University, shown diagrammatically and described in § 39, the main difference being in size and in the position of the steelyard relative to the centre line of the machine. Owing to the smaller capacity an intermediate lever is omitted in the 100-ton machine and the main steelyard is placed in the same plane as the test-piece instead of at right angles to it.

The 100-ton machine is designed for a working pressure of 1120 lbs. per square inch with a ram having a stroke of 42 inches. The tension specimen has a maximum stretched length of 15 feet 6 inches and the compression specimen may be any length up to 15 feet. For bending tests the specimen may be arranged to suit a maximum span, also of 15 feet. The cross-beam is clearly shown in the figure, it carries sliding presser feet at each end for beams and a fixed platen at the middle for columns.

The steelyard is provided with three scales, each of which is traversed by its respective poise weight. The first scale ranges from zero up to 25 tons, by 0·001 ton, and is traversed by the right-hand poise. When this poise is coupled to the one next to it, they travel together, and read against a scale marked from zero to 50 tons by subdivisions of 0·01 ton.

When the three poises are all coupled together, they traverse a third scale, which ranges from zero to 100 tons, by subdivisions of 0·01 ton. This provision enables the machine to give finer subdivisions when tests requiring lower loads than the maximum are necessary.

100-ton Buckton Horizontal Machine.—A good indication of the build of this machine is given by Fig. 48. Essentially the arrangement is that of the Werder machine with compound levers substituted for the single lever.

The centre (second) straining head can be adjusted in the notched frame, which is connected to the hydraulic ram, to take test-pieces in tension up to 13 feet in length (stretched length 15 feet 6 inches) and in compression up to a length of 15 feet 6 inches.

The cross-head, at the steelyard end of the machine, to which the other end of the tensile test-piece is connected communicates

the load to the weigh lever through a bell crank lever and vertical link. Short compression pieces can be tested between the "steelyard" cross-head and the end of the ram.

The machine is hydraulically controlled. The stroke of the ram is 30 inches and its return is operated by an independent hydraulic cylinder.

§ 39. **Large Horizontal Machines.**—In order to carry out tests on built-up structural members of a practical size, machines of large capacity are required, and, for this purpose, no machine of less than 300 tons is of much use. Excluding chain-testing machines, the best examples of large horizontal machines built in this country are :—

Kirkaldy's machine of 400 tons, built in 1866.

The 300-ton machine of the Conservatoire des Arts et Metiers, at Paris, built by Messrs. J. Buckton & Co. in 1904.[9]

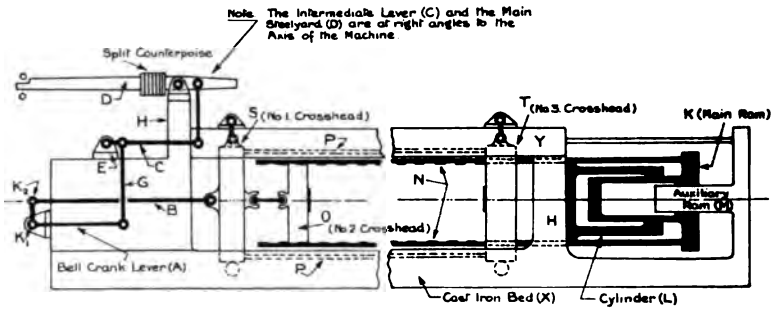

FIG. 49.—Diagram of the Birmingham University 700,000 lbs. testing machine.

The Avery Machine [10] of 700,000 lbs., installed at Birmingham University in 1909.

The Birmingham University 700,000 lbs. Testing Machine.—This is a universal machine with a capacity of 700,000 lbs. and takes tension bars 28 feet long and columns 30 feet long. The span for bending tests is 20 feet and the wedge grips take a maximum size of 6 inches × 2½ inches flat or 3¾ inches diameter.

A diagrammatic view of the machine is given in Fig. 49.

The machine has a ram (K) at one end and the lever system (D) at the other. The heavy cast-iron bed (XX) has substantial standards (HH) at either end whose tops are connected by horizontal columns (YY) with the distance, of about 40 feet, between them without intermediate support. There is therefore a clear span along the top and sides enabling heavy test-pieces to be lowered in position by the traveller running overhead. To one

standard the cylinder (L) is bolted while the lever system is fixed to the other.

The load is applied by hydraulic pressure. At Birmingham the town pressure of 100 lbs. per square inch is available for low load tests and gives a total thrust of 35 tons. For the full capacity of the machine an accumulator supply of ten times the pressure is used. The diameter of the ram is 32 inches and its stroke 66 inches. The main cylinder (L), bolted to the standard, forms part of the machine frame and the main ram (K), having an internal diameter of 20 inches, moves over an auxiliary fixed ram (M) whose function is to provide for the return of the main ram after the test is completed. The main ram is driven forward by admitting low pressure water behind the fixed ram.

The load on the ram is communicated to the travelling cross-head (O) by means of four notched racks (N), sliding in the frame of the machine, which are fixed to the head of the ram and into which the cross-head (O) is keyed in any desired position.

One end of the test-piece is fixed to the cross-head (O) and the other end to the cross-head (T), for compression and the cross-head (S) for tension. Cross-heads (S) and (T) are suspended from knife edges on the top of the frame (Y) and are connected by tension rods (PP) which, when cross-head T is in use, transmits the load to the lever system through cross-head S and the main link (B). The main link (B) pulls on the top knife of a bell crank lever through a hardened steel bearing block. Thus for compression the load is communicated to the weighing apparatus from the ram by way of: (1) sliding racks (NN); (2) travelling cross-head (O); (3) the test-piece; (4) the floating cross-head (T) and rods (PP); (5) cross-head (S); and (6) main link (B).

The weighing apparatus consists of a bell crank lever (A) whose principal knife edge (K_1), 5 feet long, thrusts against a plate fitted in the bed of the machine. The load is applied by the main link (B) on to a knife edge (K_2) similar to the principal knife edge but a short distance above it and forming with it the short arm of the lever. The intermediate lever (C) and the main steelyard (D) are at right angles to the axis of the machine. The former has its fulcrum on a substantial casting (E) fixed to the bed of the machine, and the load from the bell crank lever is transmitted to it by the link and shackles (G), while the latter has its fulcrum supported by a column (H) on the side of the machine.

The split counterpoise system (see § 34) has been adopted in

order to obtain an open scale for small loads. In this case it is divided into seven equal poises giving, separately, a maximum load of 100,000 lbs. and when combined the full load of 700,000 lbs.

The counterpoise can be moved by hand or operated mechanic-

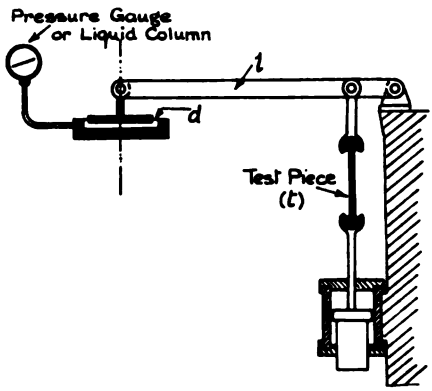

FIG. 50A.—Thomasset's testing machine.

ally through a screw and all the movements are controlled by one operator at the lever end of the machine.

§ 40. **Diaphragm Machines.**—Diagrammatic sketches of diaphragm machines are given in Figs. 50A, 50B and 51. Fig. 50A represents the Thomasset machine,[2] constructed about the

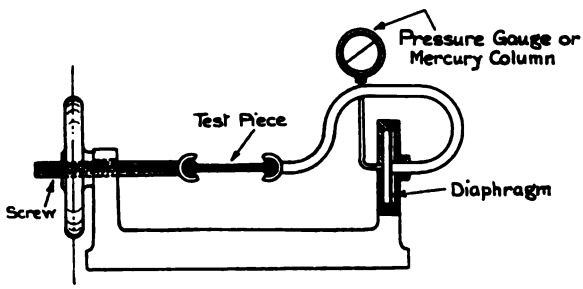

FIG. 50B.—The Maillard principle (used in Bailey's wire testing machine).

year 1872, in which the load is communicated through the test-piece (*t*) to a lever (*l*), the end of which bears on to a diaphragm (*d*). The pressure of the lever on the diaphragm is balanced by fluid pressure, the amount of which is measured by a gauge.

The Maillard machine (Fig. 50B) is similar to that designed by

Thomasset except that the intermediate lever is dispensed with, the pressure being taken directly on the diaphragm which is consequently much larger. The Maillard principle is adopted by Messrs. W. H. Bailey & Co. in their 5000-lb. Ster-hydraulic tester, and is a very convenient arrangement for testing small specimens. The load is applied to the back of the diaphragm and the pressure in the diaphragm chamber is measured by a pressure gauge or mercury column.

Fig. 51 represents the Emery machine, the first example of

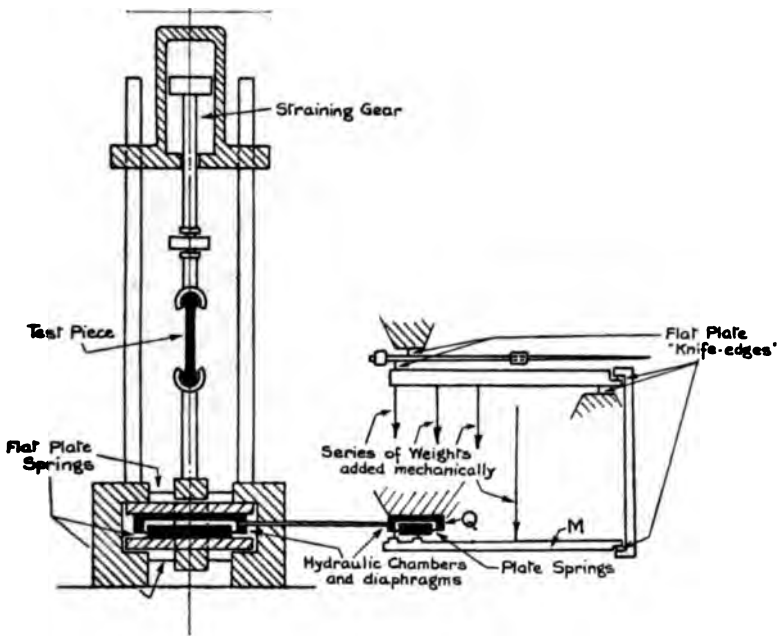

FIG. 51.—Diagram of Emery machine.

which was completed in 1879; it is really a compound lever machine with an hydraulic lever introduced between the test-piece and the weighing apparatus. The pull of the test-piece is communicated to a diaphragm. It is transmitted from this to a reducer (Q), the pressure on which is balanced by the lever system.

Emery Machines.—The first Emery machine owes its origin to the United States Board for testing steel, iron and other materials, who entered upon their work in 1875. One of the most important actions of the Board was the acquisition of an

800,000-lb. testing machine which they ordered from A. H. Emery of New York. This was completed in 1879 and is one of the largest and most accurate testing machines in the world. Unwin, after inspecting an Emery machine, said: "The merit of the Emery machine was that, while it had been made as much more delicate and sensitive than an ordinary machine as a chemist's balance was in comparison with grocer's scales, this result had at the same time been obtained by means which rendered the more sensitive machine less liable to injury, less liable to wear, and less liable to get out of order, than the ordinary machine".

The principal peculiarities of the Emery machine are:—

(*a*) An arrangement of hydraulic chambers and diaphragms able to receive large pressures and shocks without injury and to transmit them to a convenient point for measuring and recording.

(*b*) The replacement of knife edges with thin blades of steel. These were introduced to "absolutely eliminate friction and to preserve indefinitely the fulcrum intervals or distances precisely as first adjusted, and to resist and transmit all the pressures and shocks to which the fulcrums are subjected without in the slightest degree impairing their sensitiveness or durability".

Numerous machines have been made in the United States since 1879 on the Emery principle. Figs. 52 and 53 show particulars of the more important working parts of a 300,000-lb. vertical Emery testing machine; detailed drawings are given in a paper by Mr. Towne.[3]

300,000-lb. Emery Machine (Figs. 52 and 53).—*Straining Gear.*—A tension test-piece (A) (Fig. 53) is shown between the shackles (U and L) of the machine. The upper shackle (U) is attached directly to the ram (P) of the straining press, which is carried by two main adjusting guide screws (M) rising from the bed of the machine (F). The vertical adjustment is effected by means of the nuts (N) which are geared together and are rotated, through a shaft and bevel gearing, by a handle (X).

The fluid pressure is conveyed to the ram by the pipes (T_1 and T_2) which have swivel joints to allow for adjustment of the straining cylinder.

Hydraulic Lever.—The lower shackle (L) is secured to a yoke consisting of two blocks (H and B) connected by four steel bolts. In this yoke the hydraulic support (S) is placed between the two beams G_1 and G_2. Thus the load is transmitted directly to the hydraulic support through the yoke and beams. The upper

block (H) acting on beam G_1 for compression and the lower block (B) communicating the tensile load through beam G_2.

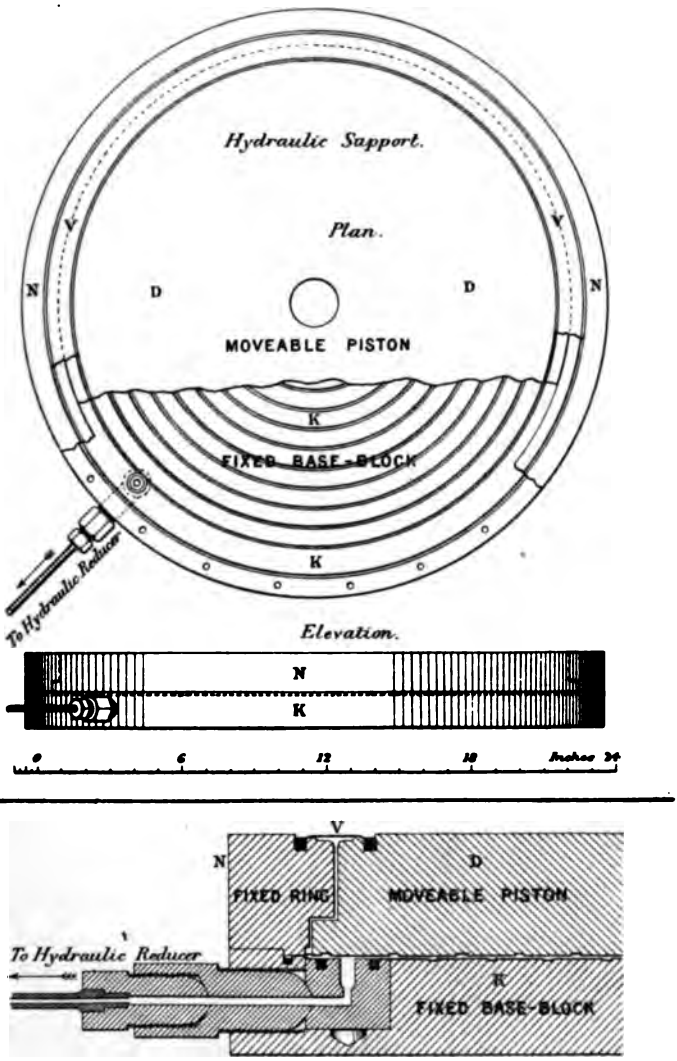

FIG. 52.—Hydraulic support for the Emery testing machine.

The yoke is secured in its proper position by flat plate springs which hold it steady laterally while leaving it free to move

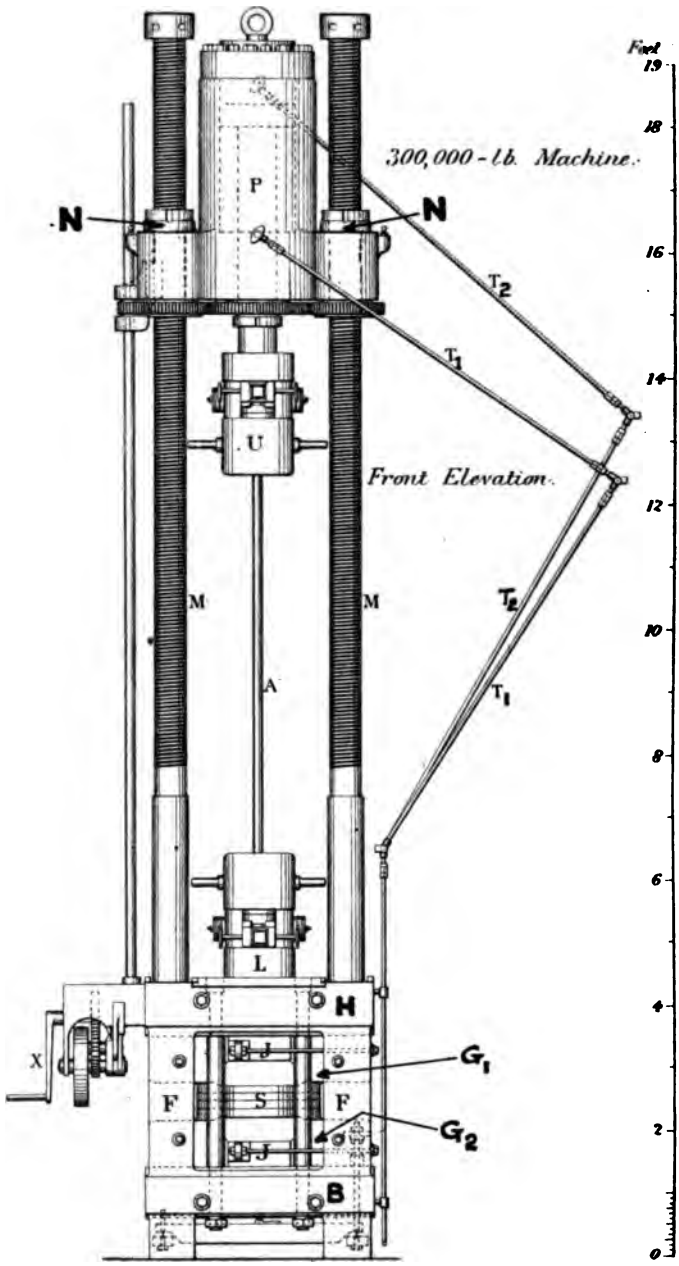

FIG. 53.—Arrangement of Emery testing machine.

vertically through the small range desired. The hydraulic support (S) is shown in detail in Fig. 52 and consists of a piston (D) which can move vertically 0·001 inch in a fixed ring and base block (N and K). A space of 0·1 inch is allowed between the piston (D) and the ring (N).

The lower surface of the piston and the upper surface of the base block are turned with annular grooves and are lined with soft sheet brass 0·005 inch thick. The linings form a sac by being interlocked as shown in the diagram. The piston (D), while permitted to move vertically, is secured against lateral motion by an annular diaphragm (*v*), at its upper surface, and the exposed portion of the working diaphragm or upper portion of the brass sac at its lower face which acts as a flexible hinge or joint. The sac is filled with alcohol and glycerine or refined kerosene oil, and the load when applied to it is transmitted to a smaller hydraulic chamber or reducer (Q) (Fig. 51), containing a similar thin film of liquid, where it is balanced by the lever weighing apparatus.

Weighing Apparatus.—The maximum load of the machine is thus reduced to a maximum of 10,000 lbs. on the reducer and this is all the load that is conveyed to the fulcrum plate of the main lever (M) (Fig. 51) of the weighing apparatus. Thin pieces of tempered steel are used instead of knife edges and are forced, under a pressure of about four times the working load, into the pieces that they connect. The relation of the beams, which have a total multiplication of 20,000 to 1, is shown in the figure. The total reduction of load is 60,000 to 1, so that very small weights are all that are necessary to keep the levers horizontal.

Calibration.—The hydraulic support is tested with known loads, applied by a "rating machine," up to the maximum capacity of the Emery machine. The exact weight required on the weigh lever to balance a known load on the machine is thus found by actual test, and the poise weights are carefully adjusted in accordance with this calibration.

The rating machine is a carefully constructed dead weight loading appliance. The weight was produced from standard weights accurately adjusted at the Bureau of Standards, Washington.

§ 41. **Machines with no Weighing Device.**—Machines in this class are those in which the load is applied by a fluid press and the stress in the specimen is calculated from the pressure on the plunger.

An objection which has been raised to this method of test is

that errors are introduced into the results owing to the variability of the friction caused by the ram packing. This objection has now been overcome, in the machine constructed by Messrs. Alfred J. Amsler & Co., by using oil as the fluid together with an accurately fitted ram and cylinder with small clearance, thus eliminating the packing friction.

Amsler Testing Machine.—A 50-ton universal machine of this make is shown in Fig. 54. Each installation consists of three main parts:—

(1) The press or actual testing machine (P).

(2) The oil pump for producing the pressure (O).

(3) The pendulum dynamometer for measuring the load from the oil pressure in the pressure cylinder (D).

The Press.—The press is fixed to the top part of the machine, and the movable cradle carrying the upper grips is freely suspended from the ram by two rods connected by a cross-head which rests on the top of the ram. The bottom of the cylinder of the press is held rigidly to the base of the machine by four round columns, which are made heavy enough to carry the superstructure and to carry the maximum load without deformation.

The base itself does not take any of the load applied to the test-bar (T), it is required merely as a support for the machine and to raise the working parts to a convenient height above the floor level. It is made in the form of a hollow iron casting with an opening in the front for the recovery of the fractured test-pieces.

The ram of the press is fitted in the cylinder with such precision that no collar or cup leather is required to ensure a sufficiently oil-tight working. The small amount of play which the ram has in the cylinder allows a slight infiltration of oil to take place between them, this makes the movement of the ram in the cylinder very easy, eliminating friction and allowing an exact measurement of the total stress to be made. The ram can be rotated by a handle so that by occasionally moving it through a small angle the formation of ridges, etc., is avoided.

Oil Pump.—The press is operated by oil pressure produced by a high pressure pump driven by an electric motor from a countershaft (for small machines a hand drive can be employed). The arrangement of suction and delivery of the oil is such that if all the valves are kept closed the oil is automatically short circuited back to the reservoir which is carried on the pump stand. There are also returns for the oil to the reservoir from the top of the cylinder due to leakage, and for the released oil from under the ram.

Water pressure may be used to work the machine by making

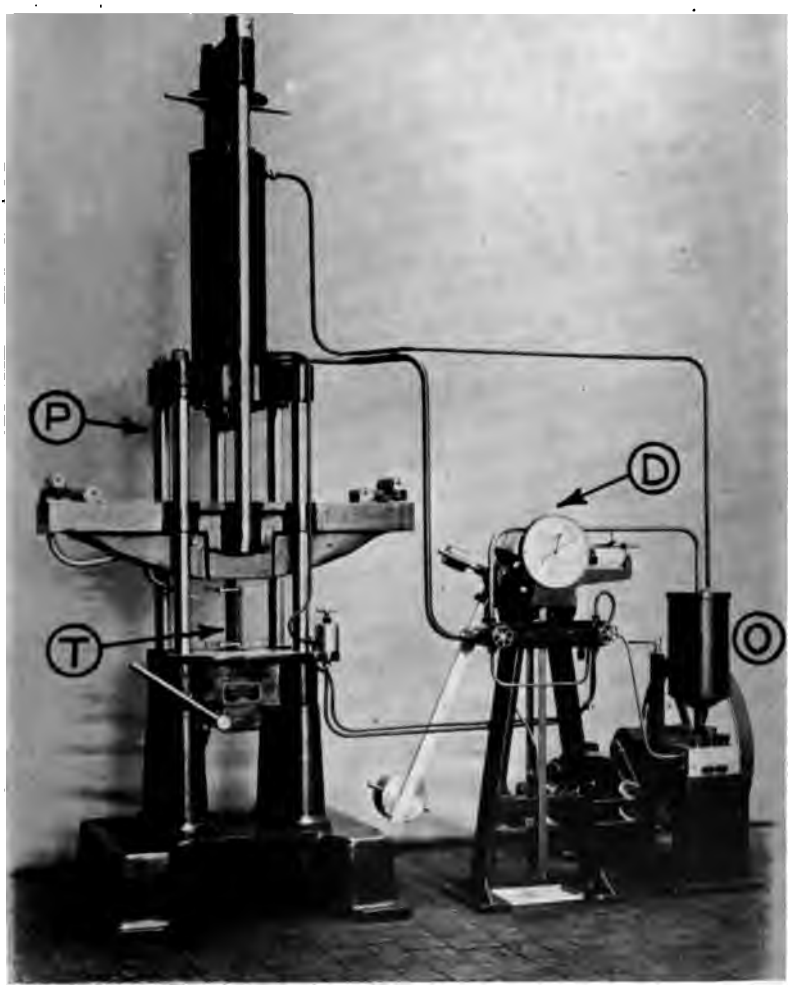

FIG. 54.—Amsler's 50-ton universal testing machine.

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FIG. 55.—Pendulum dynamometer for Amsler testing machine (front view).

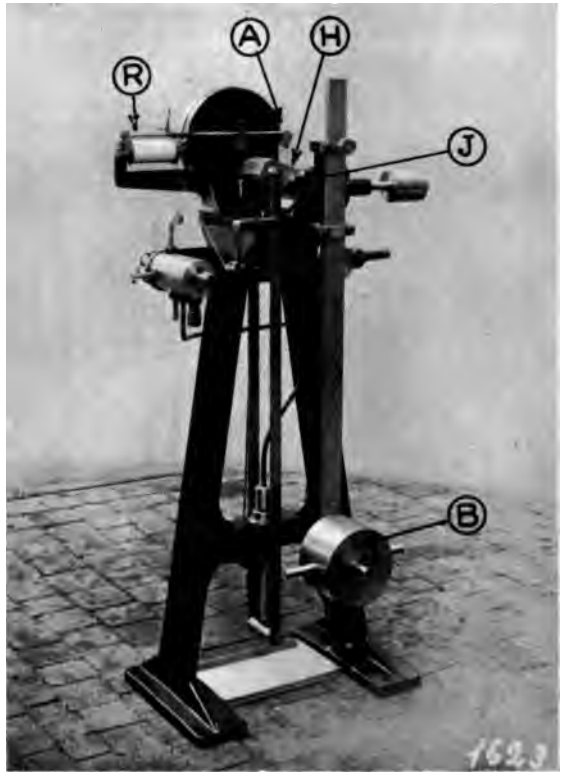

FIG. 56.—Pendulum dynamometer for Amsler testing machine (back view).

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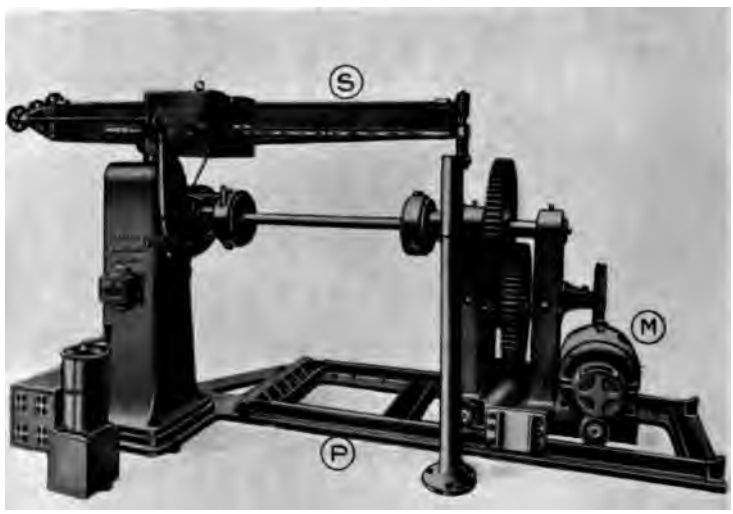

FIG. 58.—150,000 lbs.-ins. torsion machine.

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arrangements for transforming into oil pressure for working the press.

The Dynamometer Apparatus.—The measurement of the load is made by means of a pendulum dynamometer. The oil from the high pressure pump is admitted to the straining cylinder through the dynamometer, so that the actual pressure in the cylinder is shown by the pointer which is operated by the dynamometer.

The pendulum dynamometer is a modification of the dead weight gauge which is used for calibrating pressure gauges, the pendulum arrangement being used to automatically balance the load on the plunger, as shown in Figs. 55 and 56. The oil pressure is applied to a plunger (P), which is kept slowly revolving during the test by the pulley P_y, from which it is transmitted to a yoke (Y) connecting two vertical rods G_1 and G_2. The tops of these rods are attached through a ball-bearing coupling to a short block lever (H), which is rigidly secured to a shaft (J) mounted in ball-bearings in the manometer frame. The depression of the block (H) by the pressure causes the heavy pendulum (B) to be deflected until it assumes a position of equilibrium. The point of suspension of the pendulum (C) can be altered so as to increase the sensitiveness of the machine, the connection to the recording gauge being adjusted at the same time.

The pendulum operates a pointer on a dial by means of an arm and rod (A). An autographic recording apparatus (R) is also provided.

As a rule each testing machine is accompanied by a pump and separate dynamometer, but it is possible for several machines to use a single pump, if worked in conjunction with an air accumulator, and a separate dynamometer for each machine.

§ 42. **Torsion Testing Machines.**—Many universal testing machines of the lever type are fitted with a special shackle for applying torsional load as illustrated diagrammatically in Fig. 57, in which the torque is applied by a worm and worm-wheel A and measured by running the jockey weight B along the lever arm C. It is, however, usually more convenient to have a separate machine for the test.

(i) **Avery Torsion Machines.**—Fig. 58 shows a machine of 150,000 lbs.-ins. capacity embodying the method of test mentioned above.

This machine will apply torsion tests to unprepared bars, up to a maximum of 3 inches in diameter, and 6 feet in length. The twisting strain is effected through the medium of an electric

motor and gearing (M), and the indication of the torque is obtained by a lever which communicates the load to the steelyard (S), where it is balanced off in the usual manner. The straining gear is mounted on a movable platform (P) so as to be able to accommodate different lengths of specimen.

The steelyard is graduated from zero to the full capacity of 150,000 lbs.-ins. by subdivisions of 1000 lbs.-ins. Readings on a Vernier can be taken to 100 lbs.-ins.

The chucks by which the specimen is held are of the self-centreing type, enabling specimens down to the minimum of $\frac{3}{4}$ inch diameter to be tested. The chuck at the weighing end of the specimen is permitted to move axially to accommodate the variations in length of the specimen produced by the test.

It is sometimes convenient to be able to twist a bar in both

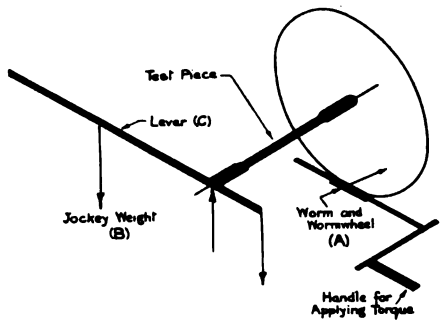

FIG. 57.—Method of applying torsion stress.

a forward and a reverse direction and measure the twisting moment applied.

A machine, giving a maximum torque of 10,000 lbs.-ins., in which this can be carried out is shown in Fig. 59.

It is a hand-power machine the specimen being prepared at each end with keyways which fit into sockets. The socket at the weighing end of the specimen is carried in ball-bearings and has supported upon its spindle a cross lever, with knife edges at each end. According to the direction of the twist these knife edges come alternatively into play, and pull upon small intermediate levers which communicate the load to the steelyard. The steelyard is provided with a poise, adjustable in weight, and small counterweights are provided at the far end of the steelyard to produce equilibrium when varying the poise.

(ii) **Buckton Torsion Machine.**—A machine employing the

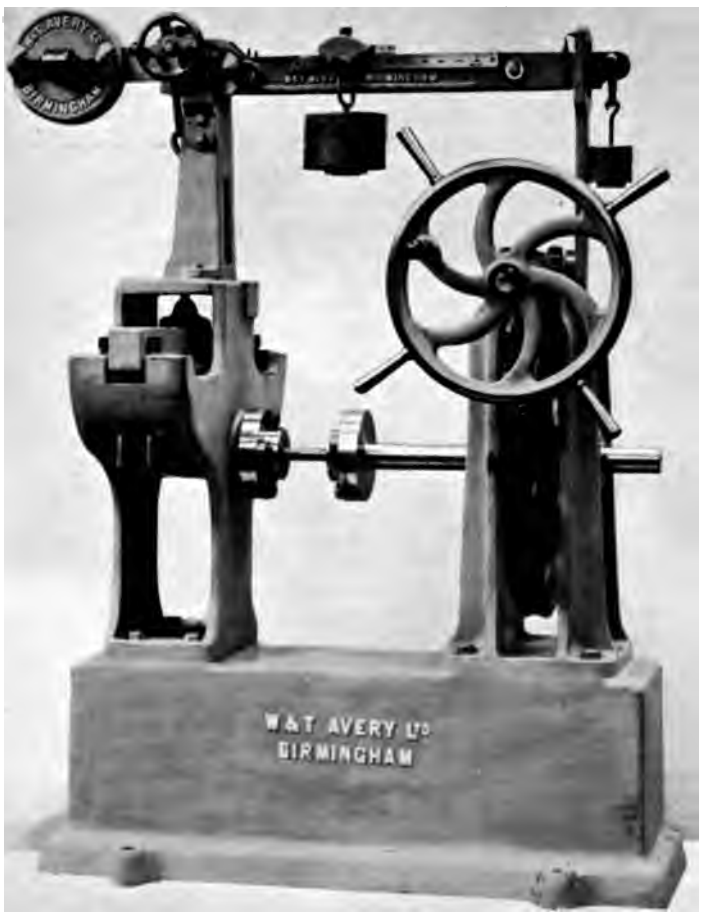

FIG. 59.—10,000 lbs.-ins. reverse torsion machine.

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principle shown in Fig. 57 has recently been supplied by Joshua Buckton & Co. to the East London College. This machine has many improvements over the older designs by the same firm and is especially suitable for accurate determinations of the modulus of rigidity and limit of proportionality in torsion.

(iii) **Thurston's Torsion Machine.**—A neat little machine,

FIG. 60.—Thurston's autographic torsion testing machine.

designed by Prof. Thurston, and made by W. H. Bailey & Co., Salford, is illustrated in Fig. 60.

The test-piece is placed between two independent jaws, one of which is rotated by hand through a worm and worm-wheel. The twist is communicated through the test-piece to the other jaw on which a weighted pendulum is attached. The resistance to deflection of the pendulum causes a torque to be applied to the test-piece, and the angle of deflection of the pendulum is a

measure of that torque. The history of the test is recorded autographically on a chart attached to a drum which is secured to that jaw which is moved by the gear wheel. The deflection of the pendulum moves a pencil, which is secured to it, over a guide curve fixed to the frame of the machine in such a way that the movement perpendicular to the plane of rotation (that is, the height of the curve) is a measure of the torque, while the length of the curve is proportional to the angle of twist of the test-piece.

Fig. 61 shows the form of test-piece used, method of fixing in the jaws and templates for ensuring that the test-pieces are of the correct dimensions.

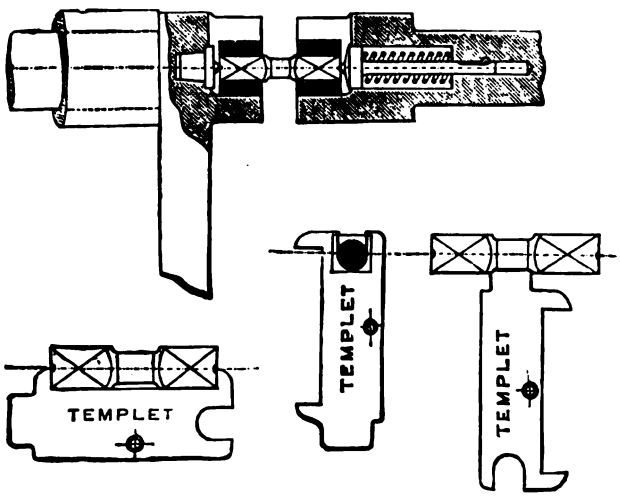

FIG. 61.—Test-piece and templates for Thurston's torsion machine.

(iv) **Amsler's Torsion Machine.**—Alfred J. Amsler & Co. also make a pendulum torsion machine (300 kilogrammetres).

In this apparatus the twisting moment applied by the straining gear is balanced by a heavy pendulum being raised through an angle. The movement of the pendulum is communicated to a pointer on a dial which is calibrated in terms of the torque.

§ 43. **Transverse Testing Machines.**—Although a transverse testing shackle always forms part of a universal testing set, most testing machine manufacturers supply special machines particularly suitable for testing cast iron by cross breaking. These machines enable cast-iron foundry bars to be tested rapidly, and give reliable information as to the mechanical properties of different mixtures.

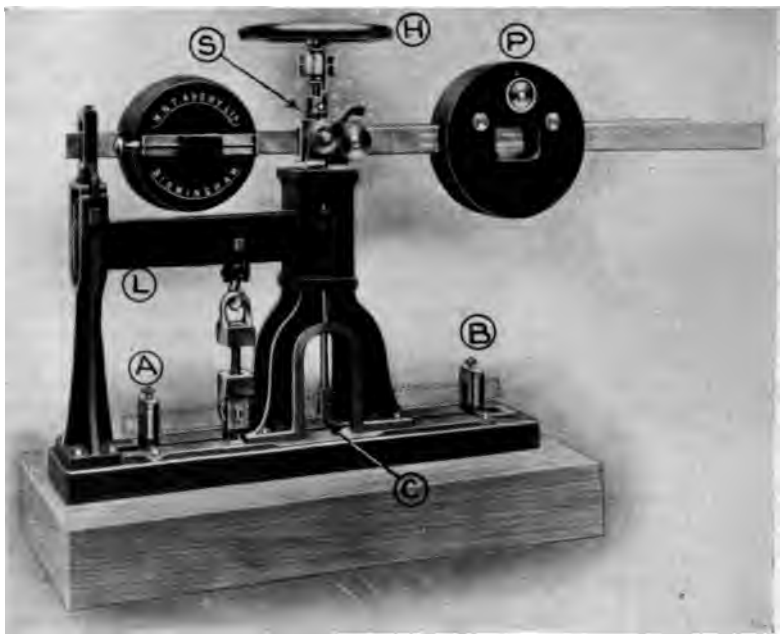

FIG. 62.—Transverse testing machine, including provision for tensile tests on cast iron.

[*To face p.* 73.

The Avery improved foundry testing machine for cast iron is shown in Fig. 62. The foundry test-bar which may be 2 inches by 1 inch in section, on a span of 36 inches, or 1 inch by 1 inch section on a 12-inch span, is secured in two dogs (A and B) which are set to the specified span. A stirrup (C) on the centre of the bar specimen applies the load to the steelyard through the medium of a hand-wheel (H) at the top, the poise (P) being moved out by a screw and gearing (S), to maintain equilibrium.

The machine reads from 0 to 50 cwt., by 28 lbs. divisions, for the transverse test. The deflection of the bar under the load can be measured by a micrometer type of deflectometer attached to the screw (S), which gives readings to 0·001 inch.

In order to make it a complete tester for cast iron, the machine is fitted with an arrangement for carrying out tensile tests. Provision is made for test specimens 0·564 inch in diameter, for which size the capacity in tension of 80 cwts. allows for iron which will stand 16 tons per square inch. The upper tensile dies are attached to an intermediate lever (L), thus communicating the load to the steelyard, while the lower holder is anchored to the bed.

REFERENCES FOR CHAPTER IV.

[1] Whitworth, "Hydraulic Testing Machine," see Peet, "Proc. Inst. Mech. Eng.," 1898.
[2] Lebasteur, "Les metaux," p. 52.
[3] "Emery Machine," see Towne, "Inst. Mech. Eng. Proc.," 1888, pp. 206 and 448.
[4] "Engineering Record," Vol. LIX, Feb., 1909.
[5] "Proc. Am. Soc. Test. Mat.," Vol. IX, 1909.
[6] Barlow, "Strength of Materials," London, 1851, p. 258.
[7] Wicksteed, "Inst. Mech. Eng. Proc.," 1882, p. 384.
[8] "Werder Testing Machine," "Engineering," Vol. XXXV, June 8th, 1883, p. 530.
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[10] "Engineer," May 21st, 1909.

CHAPTER V.

TESTING MACHINE GRIPS AND SHACKLES AND CALIBRATION OF TESTING MACHINES.

§ 44. **Grips for Holding Test-bars.**—As much care should be bestowed on the design of the grips for holding the test-bars as on any of the other essential parts of the testing machine, if accurate results are required. It is important that these should be so designed that the resultant of all the forces acts along the axis of the bar for, if this is not done, the amount of the ultimate load is affected.

The usual method of ensuring that this condition is fulfilled is by arranging for some form of spherical or swivelling seating between the test-piece and the connection to the testing machine. The principal objection to most of these seatings is that they have no protection from dust, scale, or other small pieces which are apt to be scattered by the test-piece on fracture.

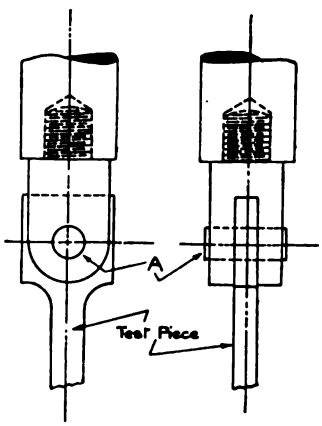


FIG. 63.—Pin grips.

In the 100-ton Buckton machine, described in § 35 (iv), large hemispherical pieces (H_1, Fig. 65) are arranged in the top and bottom holders and to these pieces the special attachments are fitted for test-pieces of various kinds.

§ 45. **Tension Shackles.**—(i) *Pin Grips.*—Fig. 63 shows the oldest method of holding the ends of plate specimens. A hole is drilled at each end of the test-piece for a steel pin (A) and the middle part of the plate is reduced in section. The relation of the size of the pin holes and the size of the heads of the test-piece to the reduced section is such that the specimen always breaks in the reduced section. This form of holder is

one of the best for small specimens provided care is taken to ensure that the pin-holes centres are accurately coaxial with the reduced part of the test-piece, otherwise the stress across the section is not uniform and the specimen tears from the edge where the stress is greatest.

(ii) *Wedge Grips.*—The ordinary method adopted for holding specimens of ductile materials is between two wedges with roughed surfaces, as illustrated in Fig. 64, but it does not necessarily ensure that the line of pull is axial. In order to obtain the best results with this method the following points must be borne in mind :—

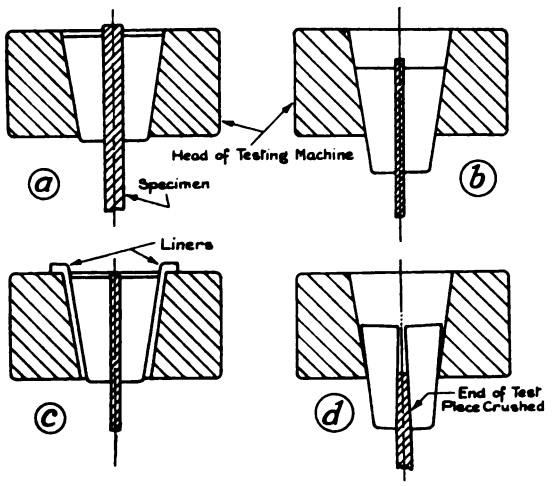


FIG. 64.—The use of wedge grips.

(1) The position of the wedges in the head, and of the test-piece in the wedges.

Fig. 64 (*a*) shows a sectional view of the testing machine head with the wedge grips and test-piece in position. The wedge grips are bearing along their full length against the head and the specimen is bearing for the full length of the wedge grips, and this is the correct condition.

Fig. 64 (*b*) shows the position of the wedge grips when the specimen is too thin and while the test-piece bears the whole length of the wedge grips, the wedge grips are not bearing their full length against the head. In this case liners are used to keep the wedges back in their proper place, as in Fig. 64 (*c*), although to obviate this difficulty most testing machines are supplied with

pairs of wedge grips suitable for various ranges in the thickness of the plate. If the specimen does not bear for the full length of the wedge grips (Fig. 64 (*d*)) there is a tendency, on the applica-

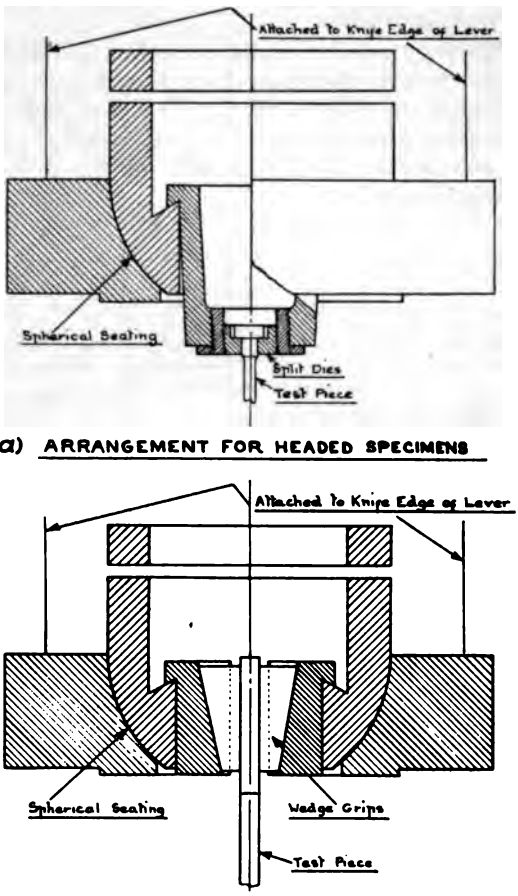


FIG. 65.—Grips for 100-ton vertical testing machine.

tion of the load, for the end of the specimen to be crushed and a force to be applied to the head which may split it.

(2) The tendency for the wedges to grip the test-piece more on one edge than the other.

This arises if the specimen is thicker on one side, or through want of proper adjustment when the holders for the wedges are split and separate from the head as in the Buckton 100-ton machine (Fig. 65 (*b*)). To avoid this difficulty Messrs. Riehlé Bros. supply wedges with a round face. In Fig. 66 (*a*) (C) are the round-faced wedge grips contained in the shackle (A). Another method for securing proper alignment is a form of ball socket liner shown in Fig. 66 (*b*).

For round or square ductile pieces the wedge grips are provided with serrated V grooves as shown in Fig. 66 (*c*).

The ends of the specimen are usually enlarged, as shown in

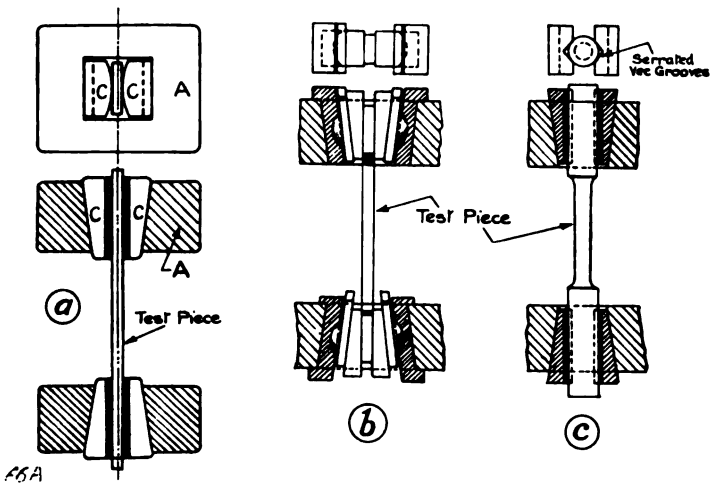


FIG. 66 (*a*).—The Riehlé round-faced wedge grips for flat or plate specimens.
FIG. 66 (*b*).—Ball socket liners.
FIG. 66 (*c*).—Wedge grips for square or round specimens.

the sketch, but with mild steel or iron this enlargement may be dispensed with.

(iii) *Self-aligning Grips.*—When testing brittle materials or for accurate experiments the alignment of the specimen is especially of importance. It is usual in these cases to use circular test-pieces with the ends to fit special spherical seated holders. Fig. 67 shows various methods of machining the test-piece and attaching to the shackles.

The effect of eccentric loading on (*a*) ductile materials is to cause a lowering of the limit of proportionality and a lowering or "rounding off" at the yield point. The drawing out or necking

of the material alters the distribution of stress across the section so that the ultimate strength of the material is not affected; (*b*) non-ductile materials is to give an unequal distribution of the stress right up to the breaking point. This causes the material to break with a stress considerably lower than the average intensity of stress on the section. Dr. Robertson found results 30 per cent. too low when experimenting on cast aluminium alloys and using inefficient shackles.

Robertson's Axial Loading Shackles for Tension.—These are shown in Fig. 68. The full load on the test-piece (T) is taken through a $\frac{5}{8}$-inch diameter hardened steel ball (B), bearing on a hardened plate (P). This plate can, very conveniently, be

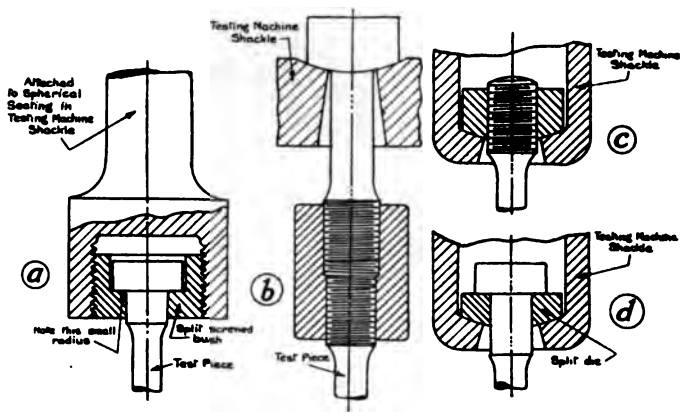


FIG. 67.—Methods of machining ends of test-pieces and attaching to the shackles.

made from a $\frac{7}{8}$-inch diameter ball, ground with two parallel flats as shown.

The ball (B) and plate (P) are held respectively in two annealed tool steel frames (F_1 and F_2). The former (F) is machined to take screwed split collars (C) for attaching the test-piece, while the latter (F_2) has a projection (E) fitted to it for connecting to the existing shackles of the testing machine.

The ball (B) is taken by a separate holder (H) and it is essential for proper alignment that the hole for this holder and the screw for the split collar should be machined at the same setting of the frame (F_2).

Avery 10-ton Shackles.—The arrangement of Avery's 10-ton shackles is shown in Fig. 69. The holder (M) is attached by a second link to a link hanging from the beam of the testing

machine. This holder consists of a forging machined to take a spherical seating (A) on which the pull of the test-piece is taken through a tool steel stem (B) and nut (C). The stem is screwed at (N) to take specimen holders of various sizes. Two forms of specimen holder are employed, viz. : (1) for headed test-pieces (D), and (2) for screwed test-pieces (E).

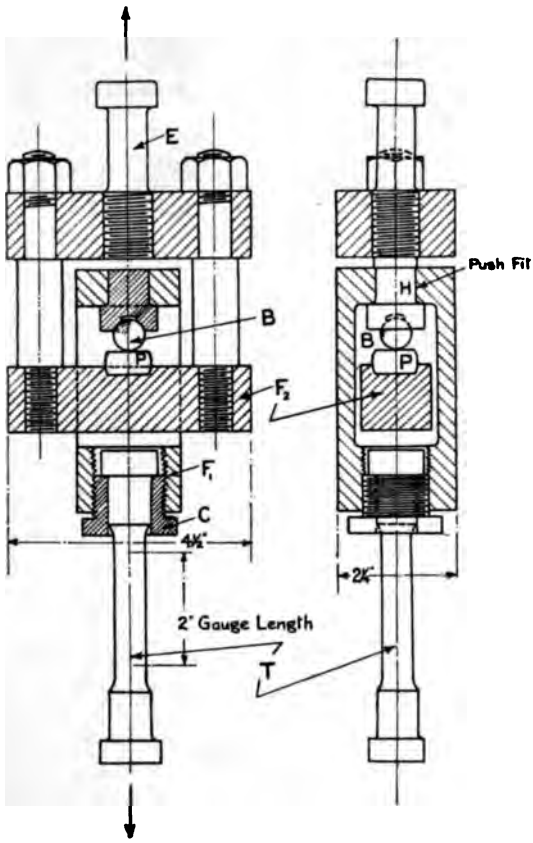
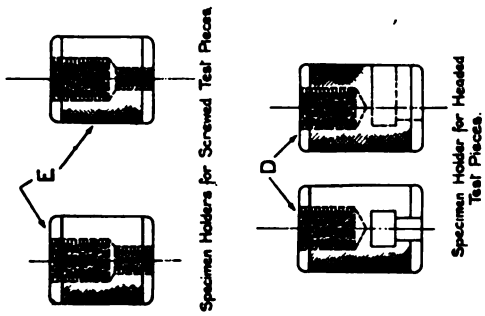


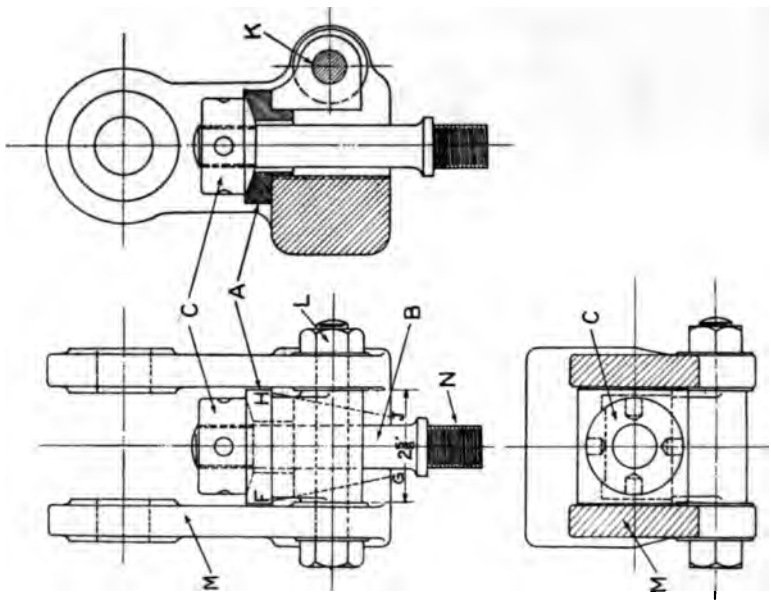
FIG. 68.—Robertson's axial loading shackles for tension.

The shackle is also arranged for use with wedges. For this purpose the nut, stem, seating, and bolt (L) are removed and wedges are inserted which bear along the surfaces FG and HJ. A handle works in the bearing (K) and is arranged with lugs which move both wedges up or down at the same time. This

facilitates gripping of the specimens and enables tests to carried out rapidly.

The top holder, for connection to the lever, is shown in figure. The bottom holder, attached to the ram straining r





works on exactly the same principle; a slide is, however, p vided for it so as to keep it parallel to the vertical test machine guides. Both holders are given in the drawing of testing machine in Fig. 35.

N.P.L. Self-aligning 10-ton Shackles.—The shackles given in Fig. 70 were designed by the authors for tensile testing, more particularly for use in experiments for the determination of the elastic limit and elastic modulus. They consist of a bolt (A) with a spherical nut (B) on one end and a holder for screwed or headed test-pieces on the other. The nut bears on a spherical seating (G) which fits into the shackle of the testing machine. The spherical seating is kept free from dirt by being closed in at the top by a plate (E) and at the bottom by a piece of wash-

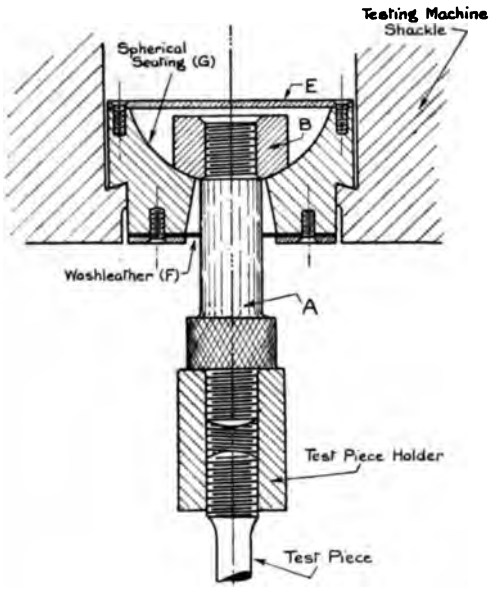


FIG. 70.—N.P.L. self-aligning shackles.

leather (F) which fits round the bolt. The washleather, although forming a dust-proof cover, allows free movement of the nut and bolt on the spherical seating. The space in the bush is filled with vaseline. These shackles have been in constant use and have been found to give every satisfaction.

§ 46. **Grips for Testing Rope.**—The gripping of ropes or cables requires considerable care in order to obtain reliable results; it is important that the grips should not damage the ends of the rope otherwise fracture will occur in the sockets.

The tests are more conveniently carried out in horizontal machines, where there is plenty of available length, than in

vertical machines. Serrated wedges (S, Fig. 71) are used for gripping both wire and hemp ropes, and, to prevent them from being damaged, wooden straps (W) of a suitable thickness and length are placed between the grips and the rope. In order to seize the rope over a considerable length these special wedge grips are made very long. The grips shown in Fig. 71 are attached to an Amsler horizontal testing machine.

Many methods have been tried for holding wire ropes in vertical machines. Some success has been attained by the use of conical dies in the shackles and sealing the ends of the wire in them, as shown in Fig. 72, with a low melting point alloy. The cable is first tightly bound with fine wire at about 5 inches from each end, the end strands are then opened, bent over and tinned. The rope is next set centrally in the dies with a little fire-clay, and a hard alloy of lead and antimony run in, forming a solid end. This method, however, is unsuccessful with copper or aluminium stranded cables with which the only satisfactory method appears to be to design the shackles so as to obtain a large area on which the wire is gripped.

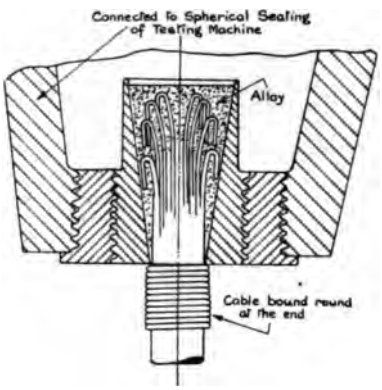


FIG. 72.—Conical die for holding cable in vertical testing machine.

A form of grip used for this purpose is illustrated in Fig. 73. These grips are circular and are turned to a taper of about 9°, they are cut into three pieces having an angle of 120° each, after the central hole has been bored, as shown in the figure. The grips are left smooth but slightly bell-mouthed.

The ends of the cable to be tested are served with soft iron wire pieces laid in position, as illustrated in Fig. 73, in order to make the outside of the cable more nearly circular, and are then tightly bound with soft iron wire strand and inserted in the grips.

These grips are satisfactory if the wedges are hammered into position, but the authors prefer to use the ordinary rectangular wedge grips (Fig. 66 (*c*)). It is found necessary, however, to give the grips a small taper and make them of considerable length (12 to 15 times the diameter of the cable). The gripping surface should be slightly serrated.

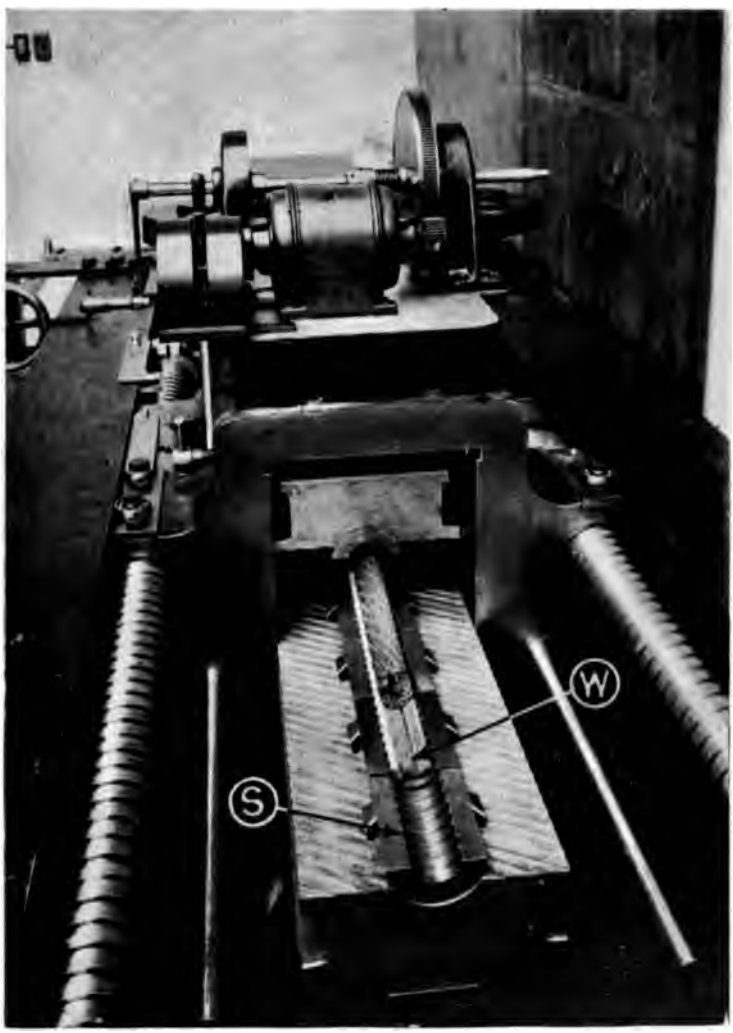


FIG. 71.—Gripping a round wire rope in an Amsler horizontal testing machine by the Deladriere system.

[*To face p.* 82.

For hemp rope and small cables a method which is largely used is to splice an eye on to each end and test by placing a steel

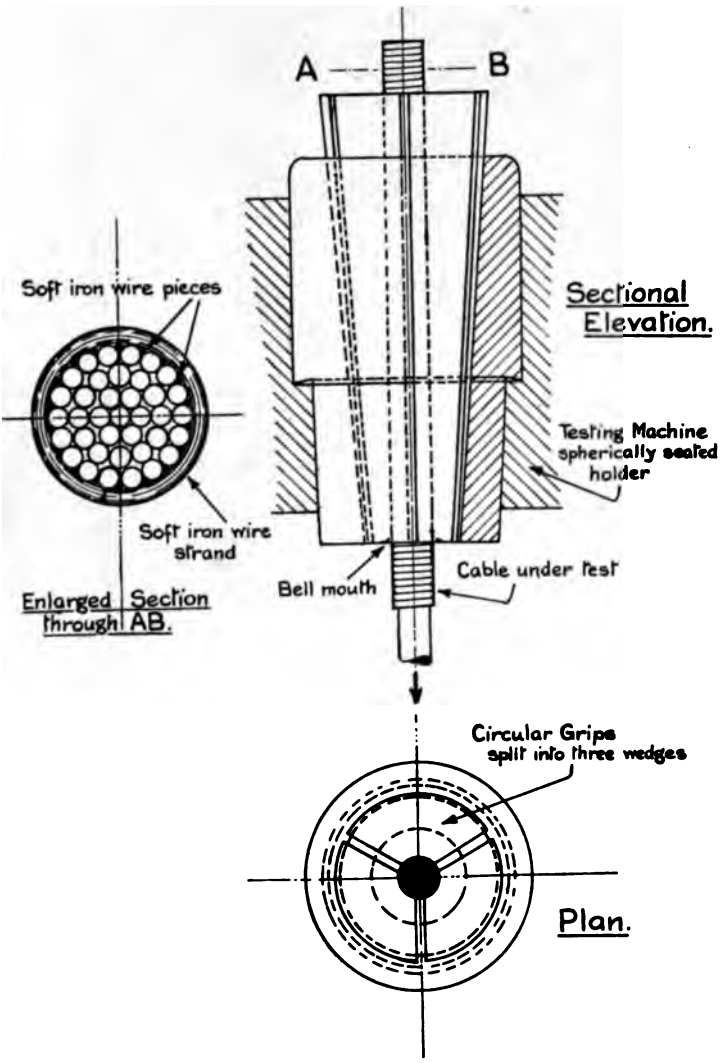


FIG. 73.—Grips for testing copper and aluminium cable.

pin through the eye. A more reliable method is to roll the ends round specially prepared helically grooved drums and clamp them. Such tools are supplied by Messrs. Tinius Olsen Testing

Machine Co. in the United States of America, or Alfred J. Amsler & Co. (Switzerland), they are costly to build but give the greater accuracy in testing such materials.

§ 47. **Grips for Testing Chains in Tension.**—For testing separate chain links or complete chains, a shackle of U-form is passed through each of the end links. The open ends of the U-pieces are then gripped in the wedges used for testing flat bars (see Fig. 74).

Where it is necessary to carry out a considerable amount of chain testing, blocks to suit the various sizes of chain are provided

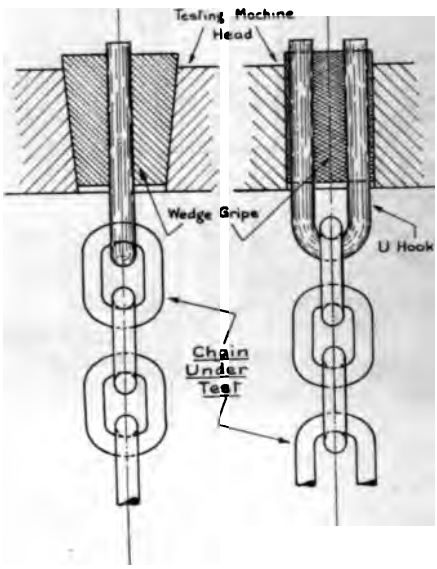


FIG. 74.—U-chain holders.

which fit into the heads of the testing machine (Fig. 75). By means of these blocks sections of a chain can be tested under a proof load, this is not possible with the U-hook method.

§ 48. **Compression Shackles.**—Spherical shackles for compression test are necessary for accurate work. These either rest on the lower shackle or hang from the upper shackle of the testing machine. Care must be employed in using any of these arrangements to ensure that the axis of the test-piece is in line with that of the bearing blocks and testing machine.

A suitable arrangement is shown in Fig. 76, this consists of a ball-bearing block fitted to the upper cross-head of the universal testing machine and a spherical seating for the lower head. It

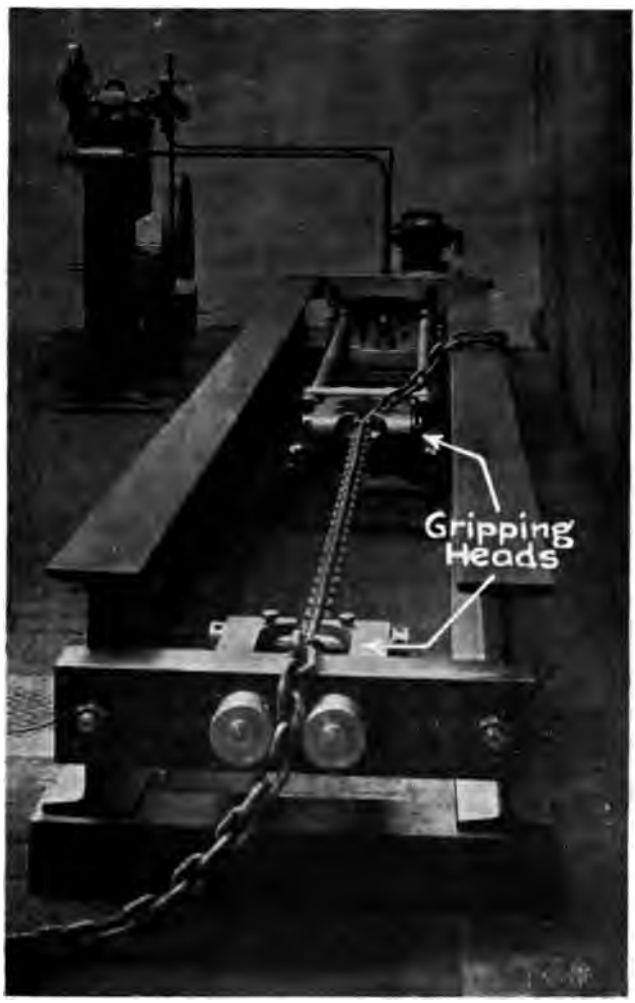


FIG. 75.—Gripping a chain.

[*To face p.* 84.

is essential that the centre of curvature of the spherical surface (O) should be in the face of the platen as shown.

Some machines are fitted with spherical seatings for both heads of the machine. There is a comparatively large amount of friction on the spherical seat (ABC), and for accurate work it is advisable to have it resting on a series of hardened steel balls let into the holder (D). A spherical seating of this kind is supplied for the 100-ton horizontal Avery machine previously described (see § 38).

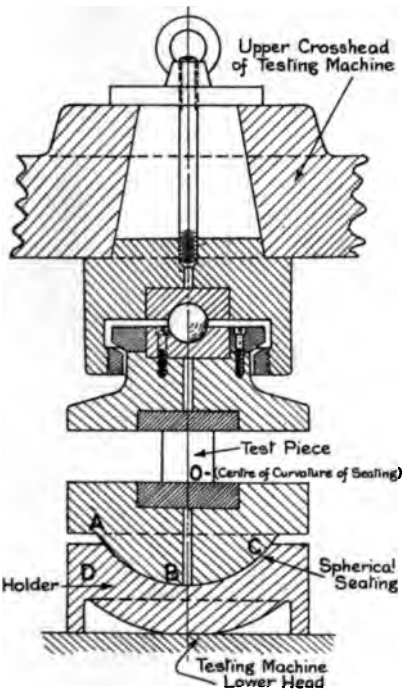


FIG. 76.—Spherical shackles for compression tests.

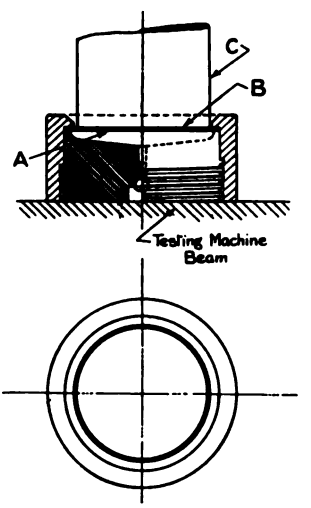


FIG. 77.—Elastic diaphragm seating.

A type of elastic diaphragm seating is shown in Fig. 77, and consists of an hydraulic sack (A) with a rubber diaphragm (B) interposed between the water sack and test-piece (C). An advantage of this arrangement is that the capping of the test-piece to obtain a flat surface is avoided and the pressure is uniformly distributed over the end. At the same time there is the disadvantage that the bedding is fluid—an objection pointed out by Unwin (see § 244).

By placing a plate on the rubber diaphragm on which the test-piece is supported, a capping is again required, but fluidity is avoided and the bearing is self-aligning

Without the plate on the diaphragm the apparatus is hardly suitable for commercial work.

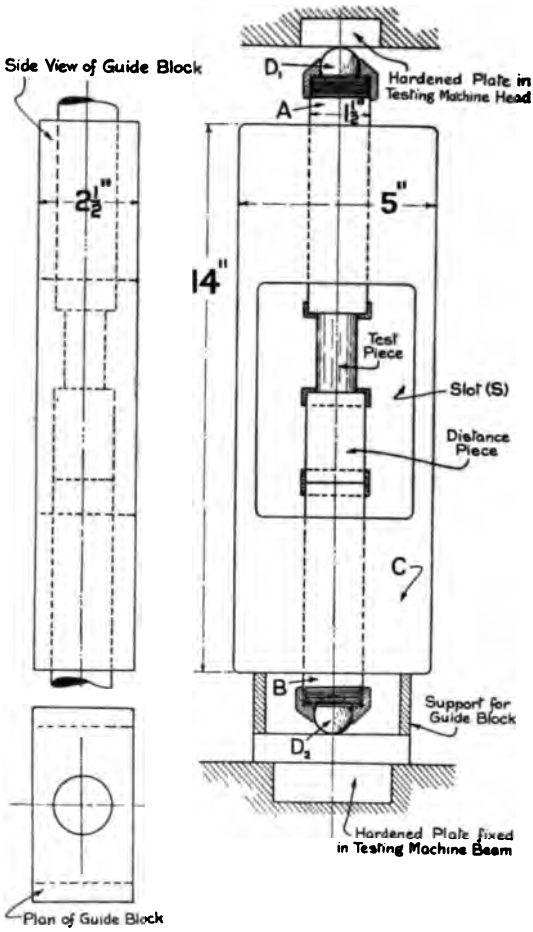


FIG. 78.—Axial loading shackle for compression tests.

Ball Axial Loading Shackles for Compression.—An apparatus designed by the authors for use when determining the modulus of elasticity and limit of proportionality of metals is shown in Fig. 78. It is in use at the National Physical Labora-

tory and was constructed to take test-pieces up to 1½ inches diameter and 6 inches in length with a maximum load of 25 tons.

It consists of two rods (A and B) 1½ inches in diameter guided in a frame (C), in such a way that their axes are coincident.

The rods are ground to be a very good sliding fit in a frame or guide block (C) and are provided with 1 inch diameter steel balls (D_1, D_2) let into one end of each. The other ends are ground accurately parallel to one another. The test-piece is placed between these ground ends and the frame is formed with a slot (S) in it so that the specimen can have a compressometer attached to it.

The testing machine shackles are supplied with hardened

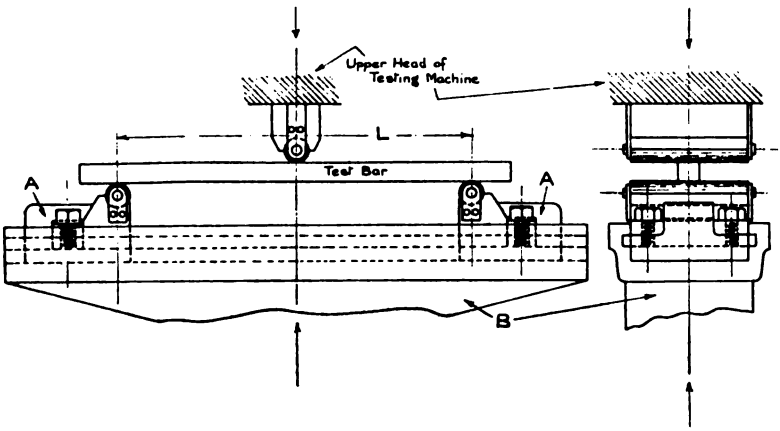


FIG. 79A.—Roller bolster supports for transverse tests.

steel plates and the load is applied through these to the balls on the ends of the guide rods. The frame can, if necessary, be moved on the rods when the specimen is under test.

In this way the load is applied to the test-piece in a perfectly axial direction and accurate load deformation curves can be obtained. The apparatus has been used with very satisfactory results.

§ 49. **Transverse Test Tools.**—Fig. 79 (A and B) shows two types of shackles for transverse testing. Fig. 79A indicates the roller bolster supports and Fig. 79B the arrangement adopted with the Buckton vertical testing machine. In the latter method it will be noted that the pressure is applied in halves, at W_1 and W_2, giving a small central span (D) of uniform

bending moment. The object of this method is to reduce local crushing of the test-piece (T). In both arrangements the standards (AA) can be adjusted to graduations on the beam (B) to give different lengths of span (L).

As timber is not homogeneous, four point loading is usually

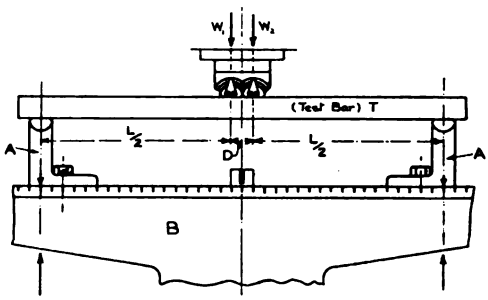


FIG. 79B.—Transverse test tools (Buckton machine).

adopted. Fig. 80 shows a suitable arrangement fitted between the compression shackles of a testing machine. This gives a span of 24 inches over which the bending moment is uniform and in which the beam theoretically bends in the arc of a circle (see § 19).

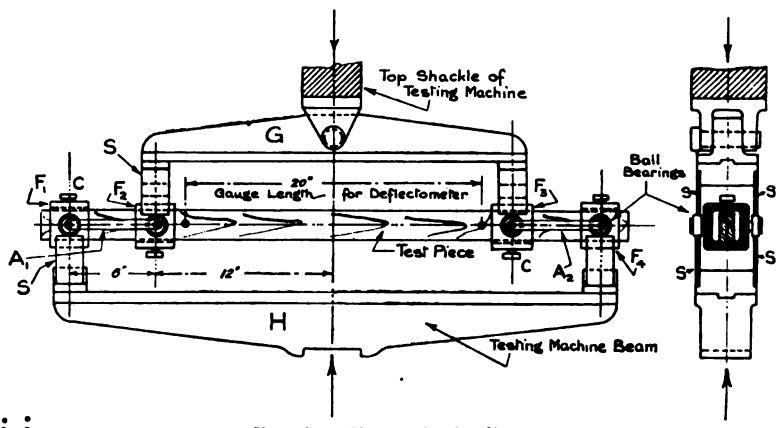


FIG. 80.—Four point loading.

Four frames (F_1, F_2, F_3, F_4) are clamped to the test-piece by special screws (C). They are arranged in pairs with distance pieces (A_1 and A_2) to keep them exactly six inches apart This distance is important as the bending moment applied.

FIG. 81.—Four point loading for timber. [*See p.* 89.

FIG. 86.—Testing machine prover on a 30-ton machine.

[See p. 91.
[To face p. 89.

is equal to half of the load multiplied by the distance. An error in this length is therefore reflected in the accuracy of the results.

Each of the frames is fitted with projections carrying ball-bearings, these rest on the supports (S) from the two beams (G and H) and rotate slightly as the test-piece is deflected.

A similar arrangement for this test, supplied by W. & T. Avery, Ltd., is illustrated in Fig. 81. It is used between the tension shackles of the testing machine. The test-piece is shown fitted with a special deflectometer.

The following points in regard to apparatus for transverse tests should be noted :—

(*a*) Rocking supports should be provided at the ends of the specimen.

(*b*) Metal plates should be provided, if necessary, to prevent a high intensity of pressure under the point of loading or at the supports.

(*c*) Deflectometers or deformeters should not be attached close to the point or points of application of the load.

(*d*) If deflections are to be observed it is advisable that the rate of loading should be such that the readings can be taken while the load is being continuously applied. If a stoppage is unavoidable the time intervals should be constant for the test.

§ 50. **Shear Shackles.**—There are two methods of applying a shear stress to materials, one by a torsion test and the other by direct shearing or punching. The torsion formula only holds for perfectly elastic bodies and if it is used for the breaking stress a figure greater than the real shearing stress is obtained.

Various methods for direct shear are in use, but with these the shear is always accompanied by a certain amount of bending and compression.

(i) *Tests of Bar and Plate.*—Fig. 82 indicates a shear test tool for round specimens. The specimen (A) is clamped to a block (B) and with the testing machine adjusted for compression testing the load is applied to the shearing tool (C). The test can be arranged so that the specimen is broken in either single or double shear. The dies (D), as well as the shearing tool, are made of tempered tool steel ground to an edge. Provision is made for wear of the tools and they are inserted in such a manner that they can be easily removed when necessary for grinding.

A similar method can be used for flat plate, the form of the shearing tool and dies requiring slight modification to that shown in Fig. 82.

(ii) *Test of Very Thin Plate.*—An arrangement for shear

tests on very thin plates or slices from a bar, used at the National Physical Laboratory, is shown in Fig. 83. The test-piece (T) is placed in a die (D) having a hardened steel facing (F). A hardened steel plunger (P), with a long bearing in the die, is placed on the test-piece. The hole in the facing (d_1) is slightly taper (the figure is exaggerated) and the end of the plunger (d_2) is made a good fit in the hole.

The gear is placed between the compression shackles of the testing machine and the load measured which enables the plunger to push a hole through the test-piece.

If t = the thickness of the test-piece and W = the load, then the shear stress = $\frac{W}{\pi d_1 t}$

(iii) *Test of Timber in Shear.*—(See Chapter on Timber Tests, § 229.)

§ 51. **Torsion Shackles.**—The easiest way of holding a

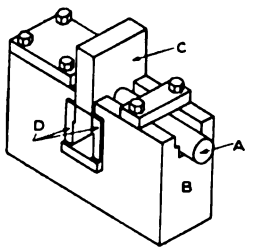


FIG. 82.—Shear tests for round specimens.

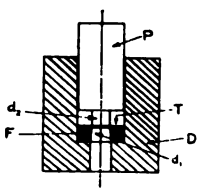


FIG. 83.—Arrangement for shear tests on thin plates.

torsion test-piece in the testing machine is to have enlarged ends, either square or round, the latter with two keyways cut in them.

Messrs. Avery supply specially designed self-centreing chucks for their torsion machine (see § 42, Fig. 58) in which tests can be made on unprepared bars.

§ 52. **Calibration of Testing Machines.**—The only satisfactory method of calibrating the readings of a testing machine is by using dead loads through the full range, such as is adopted in the Emery machines, and this method from the point of view of accuracy is above criticism.

Several devices are used to attain the same ends. If dead loads are not directly employed verification depends on a previous calibration of the device used, so that it ultimately depends on a dead load method.

Next to loading by dead weights the employment of calibrat-

ing or proving levers is the most acceptable method. An arrangement for use in a compression machine is shown diagrammatically in Fig. 84.

The levers, L_1 and L_2, carefully constructed, rest on knife edges in a double chair (C_1) which itself rests on the weighing table (T_1) of the machine. A single chair (C_2) is placed on each of the other knife edges and the upper shackle (T_2) of the machine is brought down on to this chair. A leverage of ten is generally adopted for calibrating machines up to 10 tons capacity, and a leverage of 20 up to 50 tons capacity, which is the maximum to which this method of verification is usually carried.

Details of a testing machine prover of a similar type are given in Fig. 85, while Fig. 86 shows the apparatus fitted to a 30-ton testing machine.

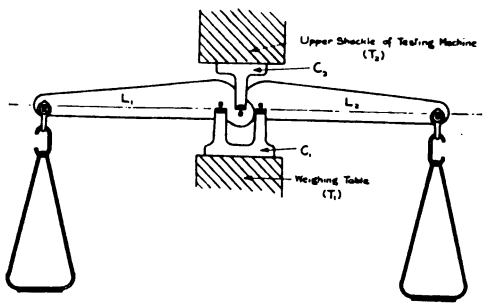


FIG. 84.—Calibrating or proving levers.

It is made and used by W. & T. Avery in conjunction with the tension shackles of vertical testing machines and consists of a lever with a 40 to 1 leverage. Thus a weight of 56 lbs. in the scale pan corresponds to a load of a ton on the machine. The apparatus calibrates a testing machine up to 30 tons.

Other methods of checking are as follows :—

(*a*) **By a Standard Test-bar** made of steel whose modulus of elasticity is known by previous experiment in a machine of known accuracy. A test-piece is turned to fit the testing machine, and of such a size that when the maximum load is applied to it the limit of proportionality of load to extension will not be exceeded. An extensometer is fitted to the test-piece, and readings of it taken at various loads shown by the testing machine indicator. These readings are then compared with those calculated from the modulus of elasticity, and a verification of

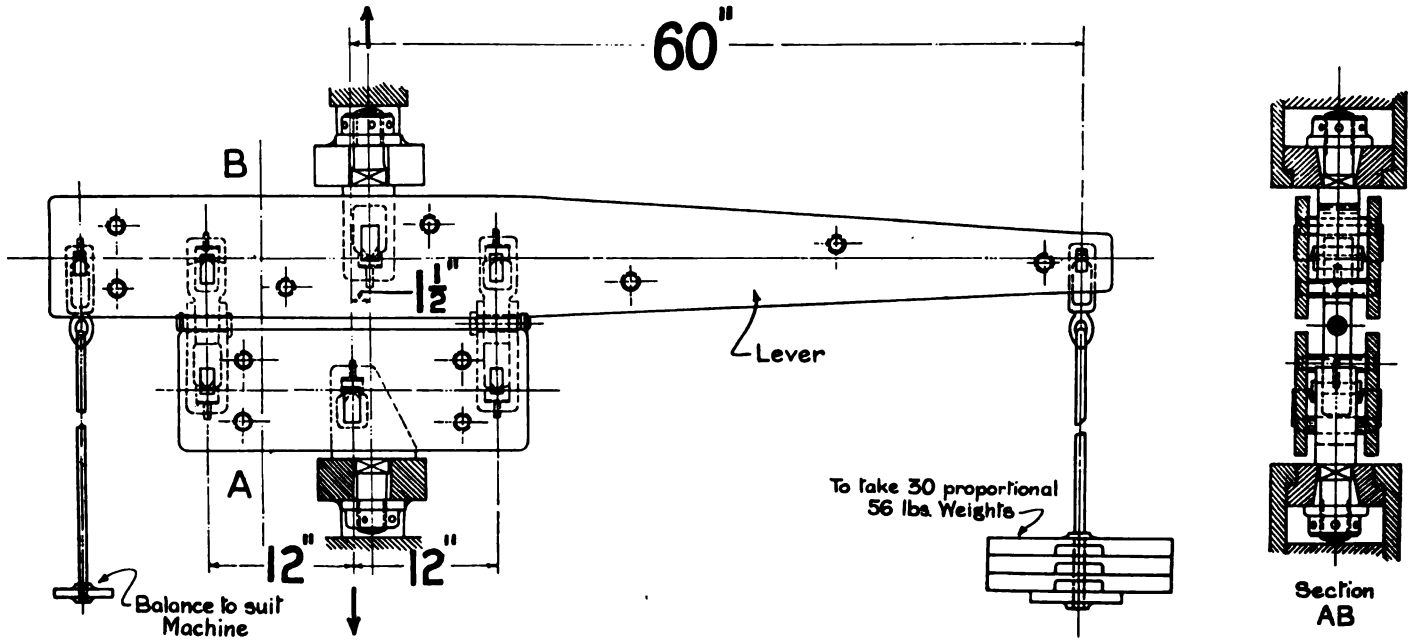


FIG. 85.—Avery 30-ton testing machine prover.

the testing machine scale obtained. This method is difficult to carry out with accuracy except by a person skilled in such work.

(*b*) **With Crushers.**—These are cylinders of copper whose diminution in length with load is known. A series of crushers are loaded in the compression apparatus of the machine with various values of the load which are noted from the machine indicator. The actual forces exerted are deduced from the diminution of length of the crushers, and these are compared with the indications of the machine.

(*c*) **By a Series of Tensile Test-pieces.**—These are made in duplicate and of varying diameters so that the largest test-pieces will take nearly the full capacity of the machine.

They are all turned out of the same bar of homogeneous material, and one series is broken in the testing machine to be calibrated, and the duplicate series tested under the same conditions in a machine whose accuracy is known.

Both methods, (*b*) and (*c*), are simple but are not available for a greater accuracy than about $\pm$ 2 per cent.

(*d*) **An Improvement of the Copper Crusher Method** has been suggested by Schule and Brunner,[1] who used wood in the form of slabs of small thickness (2 to 4 cms.) as crushers. Wood has the unique property of offering the same resistance to crushing whether tested as cubes or thin slabs. This method dispenses with all measurements of deformation which necessitate the use of instruments of precision, and by selecting wood well dried and without flaws an accuracy of 1 per cent. can be attained.

Messrs. Schule and Brunner found that the wood of Coniferæ is the most suitable owing to its regular structure. Five or six pieces of wood of each cross sectional area are tested in a standard machine as well as in the machine which is under calibration.

(*e*) **With a "Standardising" Box.**—This is an instrument supplied by Messrs. Alfred J. Amsler & Co. for quick and accurate checking of testing machines. It is essentially a hollow test-bar whose strains under loading are measured by its diminution or increase in volume. It is filled with mercury and has a horizontal capillary tube, also partly filled with mercury, attached to it on one side and a micrometer working a plunger in and out of the box, on the other side. When the instrument is stressed axially the position of the mercury in the capillary tube is altered owing to the change in volume. The position of the mercury is then restored to the zero position by the micrometer. The reading of the micrometer is calibrated under known loads and this

calibration used in conjunction with the standardising box to check the testing machine.

(*f*) The methods described above are applicable to most testing machines but with single lever vertical machines a simple test can be carried out quickly and accurately in the following way :—

As the load is weighed by a jockey weight, and as there is only one lever, it is only necessary to verify the weight of the jockey and the short arm length of the lever to ensure that the machine is reading correctly.

Weight of the Movable Counterpoise.—This can be found by lifting it from the lever with a suitable weighing machine suspended from a crane or, where this is inconvenient, by means of the lever itself in the following way. First balance the beam and adjust the Vernier to zero, then hang up a known weight from the beam at a measured distance from the fulcrum. This raises the beam and the counterpoise is run along until balance is again restored.

If W = weight of counterpoise.
W_1 = hanging weight.
l_1 = distance of hanging weight from fulcrum.
L = distance counterpoise is moved to restore balance.

Then $$W = \frac{w_1 \times l_1}{L}.$$

Distance Between the Knife Edges.—After the beam has been balanced and the Vernier adjusted to zero, a heavy weight (w_2) is hung in the shackle of the machine and the counterpoise moved forward until balance is restored.

If W = weight of counterpoise.
L = distance counterpoise is moved to restore balance.
w_2 = weight hung in shackle.
l_2 = knife edge distance.

Then knife edge distance = $l_2 = \frac{L \times W}{w_2}$.

Sensitivity.—The sensitivity of the machine can be determined by finding the greatest weight which can be hung from the shackles without causing the beam to move after it has been balanced.

J. H. Wicksteed[2] found that with a 100-ton machine in equipoise, but unloaded, i.e. with the dead weight of lever and poise equivalent to 6 tons on the knife edge, that a silk thread

breaking with a load of 3 or 4 lbs. is sufficient to raise the lever arm through its whole arc.

Zero Error.—Care should be taken to see that the zero of the machine is in adjustment before commencing a test.

REFERENCES FOR CHAPTER V.

[1] Schule and Brunner, "A New Method of Comparing the Indications of Testing Machines," "Proc. Int. Assoc. of Test. Mat.," New York, 1912.
[2] "Proc. Inst. Mech. Eng.," 1888, p. 454.

CHAPTER VI.

ELONGATION AND CONTRACTION OF AREA IN THE TENSILE TEST.

§ 53. **Ductility.**—For workshop use a bend test gives much information as to the ductility of a material and requires very

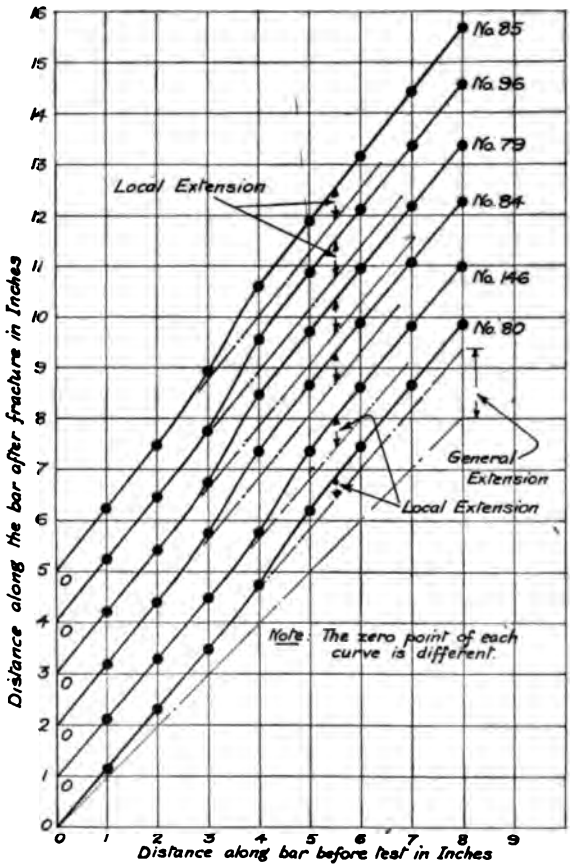


FIG. 87.—Distribution of elongation in test-bars.

little special apparatus to carry it out. The usual measures of ductility, however, are the ultimate percentage elongation or contraction of area at fracture in a tensile test.

Elongation on wires and thin sheets are difficult to measure and do not give satisfactory results. Reverse bend tests (§ 90) give a good measure of the ductility of these materials.

§ 54. **Distribution of Elongation in the Test-bar.**—If a test-piece of ductile material is marked out in 1-inch lengths and then tested in tension it is found that it breaks with a neck or waist and that the increase in length of the section including the neck is considerably more than at any other point along the bar. Observations for some bars are given in Table III, and results from them are plotted in Fig. 87, where the stretched lengths are plotted as ordinates and the original distances along the bar as abscissæ. The resulting curve is seen to consist of two parallel branches connected by an S curve, and it will be evident from the curve that the vertical distance between the two parallel branches is the local extension due to the necking of the test-piece.

In Fig. 88 the same results are plotted in another way. The increases in length in each inch are plotted as ordinates at the centre of each inch length and connected by a curve. It is seen that the rate of elongation at the fracture is very large and that the curve is nearly symmetrical about the point of fracture.

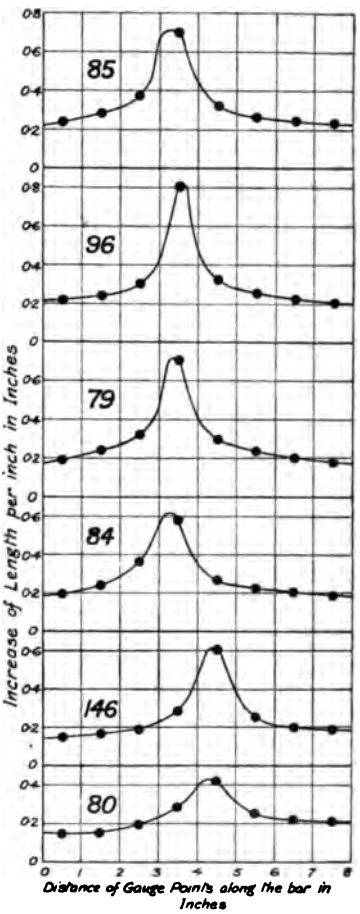


FIG. 88.—Distribution of elongation in test-bars.

From the figures in Table III the percentage elongations on various gauge lengths can be calculated. Taking the fracture as near to the centre as possible these results are given in Table IV and are calculated as follows :—

If the original gauge length = L_1
the final gauge length = L_2
the elongation = $L_2 - L_1$
and the per cent. elongation = $\frac{L_2 - L_1}{L_1} \times 100$.

TABLE III.

EXTENSIONS ON ONE-INCH LENGTHS AT DIFFERENT DISTANCES FROM THE FRACTURE.

No. of Test-piece.	Diameter of Test-piece in Inches.	Yield Stress in Tons per Sq. In.	Ultimate Stress in Tons per Sq. In.	Extension in Inches in each Inch along the Bar.								Total Extension in Inches.
				0-1.	1-2.	2-3.	3-4.	4-5.	5-6.	6-7.	7-8.	
80	1·000	14·0	21·6	·15	·16	·20	·29	·42*	·25	·22	·21	1·90
146	1·000	14·4	32·5	·15	·17	·19	·28	·61*	·25	·20	·19	2·04
84	1·000	16·3	29·9	·20	·24	·37	·59*	·27	·23	·21	·19	2·30
79	1·000	19·7	29·6	·19	·24	·32	·71*	·29	·24	·20	·18	2·37
96	1·000	16·2	23·9	·23	·24	·30	·81*	·32	·25	·23	·20	2·58
85	1·000	14·0	22·7	·24	·29	·37	·70*	·32	·26	·25	·23	2·66

* This length included the fracture.

TABLE IV.

PERCENTAGE EXTENSION ON DIFFERENT GAUGE LENGTH (INCLUDING FRACTURE) ON ONE-INCH DIAMETER BARS (SEE TABLE III).

No. of Test-piece.	Gauge Length in Inches.					
	3.	4.	5.	6.	7.	8.
80	32·0	29·0	27·6	25·7	25·0	23·8
146	38·0	33·2	30·6	28·3	27·0	25·5
84	41·0	36·5	34·0	31·8	30·1	28·7
79	44·0	39·0	36·0	33·3	31·3	29·6
96	47·7	42·0	38·4	35·8	34·0	32·2
85	46·3	43·8	38·8	36·5	34·7	33·2

It will be evident from the table that the percentage elongation is dependent upon the gauge length, decreasing as the gauge length increases, and that for strictly comparative results the same gauge length should be adopted for bars of the same diameter. Also, for strict comparability, the position of the fracture should be the same in each bar. If the bar breaks near to the end of the gauge length the percentage elongation is low. The formula for calculating the error involved has been expressed by Unwin[1] as follows:—

"Let e_1 be the percentage of elongation in a gauge length L + 2X, and e_2 the elongation in a gauge length L − 2X, the fracture being at the centre in both cases. Then the elongation in a gauge length L when the fracture is at X from the centre is $e = \frac{1}{2}(e_1 + e_2)$."

The results in Table V, taken from Unwin's paper, show the magnitude of the error. Unless the gauge mark is in the part affected by the local contraction, the effect on the per cent. elongation is small.

TABLE V.

ELONGATION PER CENT. IN EIGHT INCHES, WHEN THE FRACTURE IS *NOT* AT THE CENTRE OF THE GAUGE LENGTH.

No. of Bar.	Distance of Fracture from Centre of Bar in Inches.				
	0. Fracture at Centre.	1.	2.	3.	4. Fracture at Gauge Point.
2,361	29·2	29·1	28·9	28·1	23·5
2,362	29·5	29·5	29·5	29·1	23·9
2,363	29·8	29·7	29·8	29·2	24·4
2,364	25·3	25·3	25·3	24·4	20·2
2,365	29·0	29·0	29·0	28·5	24·1
2,390	26·7	26·6	26·6	26·6	23·2
2,391	30·5	30·5	29·7	28·3	23·5

§ 55. **Barba's Law (Elongation of Geometrically Similar Test-bars).**—The law connecting the elongation of geometrically similar test-pieces was first given by J. Barba [2] in 1880, who observed that similar test-bars deform similarly. It follows that for cylindrical specimens, if the ratio of gauge length to diameter is constant, the percentage elongation is also constant. This is

TABLE VI.

TESTS ON SIMILAR TEST-PIECES OF CIRCULAR CROSS SECTION.

No. of Test-piece.	Diameter of Test-piece "D" Ins.	Gauge Length. "L" Ins.	Ratio. L/D.	Yield Stress in Tons per Sq. In.	Ultimate Stress in Tons per Sq. In.	Extension. Per Cent.	Reduction of Area at Fracture. Per Cent.
B10D	0·550	4·60	8·36	28·41	51·69	17·4	38·4
B10E	0·420	3·50	8·33	28·88	51·27	17·2	37·5
B10F	0·330	2·72	8·24	29·01	51·70	16·8	40·8
A9D	0·550	4·60	8·36	21·26	26·52	33·2	70·4
A9E	0·420	3·50	8·33	20·51	26·27	32·8	68·7
A9F	0·330	2·72	8·24	21·06	26·90	32·2	67·8

shown clearly by the results on a mild steel and medium carbon steel given in Table VI.

TABLE VII.

TESTS ON SIMILAR TEST-PIECES OF RECTANGULAR CROSS SECTION.

Approximate Cross-sectional Dimensions of Test-piece in Inches.	Area in Sq. Ins.	Yield Stress in Tons per Sq. In.	Ultimate Stress in Tons per Sq. In.	Per Cent. Extension on Gauge Length $= C \times \sqrt{A}$. Values of C.						Reduction of Area. Per Cent.
				1.	2.	3.	4.	5.	6.	
$1\frac{1}{2} \times 3/16$	0·2813	15·5	29·2	79·4	56·6	46·3	39·7	35·6	32·4	51·3
$\frac{1}{2} \times 1/16$	0·0312	16·3	29·6	89·6	66·8	53·3	46·5	41·9	38·0	56·0

Some experiments have been carried out at the National Physical Laboratory on two sizes of geometrically similar bars of rectangular cross section in which the width is eight times the thickness. The test-pieces are all machined from normalised steel plate 0·187 inch thickness; the larger test-pieces are $1\frac{1}{2} \times \frac{3}{16}$ inches in cross section and the smaller ones $\frac{1}{2} \times \frac{1}{16}$ inches. Elongations are measured on gauge lengths equal to $c \times \sqrt{\text{area}}$, where c has the values 1, 2, 3, 4, 5 and 6, and the point of fracture is as near as possible in the centre of the gauge length. The results (given in Table VII) are the average from six test-pieces of each size. The agreement between results from the six pieces is extremely good. The smaller pieces give an elongation 13 to 18 per cent. greater than the larger ones.

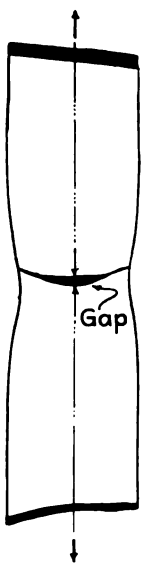


FIG. 89.—Form of fracture of rectangular test-pieces.

It should be noted that pieces of ductile material of rectangular section break in such a way that, when the pieces are placed together a gap is formed in the centre of the piece as shown in Fig. 89. The figures in Table VII include the width of this gap.

Unwin says that "in plate test bars, not strictly geometrically similar, the percentage of elongation is practically constant, if the ratio of gauge length to square root of cross section is constant. The form of cross section within somewhat wide limits, if the area is constant, does not appear to influence the elongation."

In Barba's experiments with flat plates of mild steel, 10 millimetres thick, he varies his width from 10 to 80 millimetres and finds with this range of sizes, a maximum percentage elongation on a fixed gauge length when the ratio of the width of the test-piece to its thickness is six (see Table VIII).

TABLE VIII.

BARBA'S EXPERIMENTS ON FLAT MILD STEEL PLATES.

Ratio of Width/Thickness.	Per Cent. Elongation on Gauge Length of	
	50 mm.	100 mm.
1	37·6	31
6	61·0	40·8
Increase in per cent. elongation	62	32

Gordon and Gulliver [3] give an extensive series of experiments on soft boiler plate, $\frac{1}{4}$ inch thick, in which the test-pieces are also of constant thickness but varying width. Some of the most important of their results are given in Table IX, and as regards elongation lead to the following observations :—

(i) Elongation on a fixed length increases as width/thickness is varied from 2 to 16. This increase is not at a uniform rate, as between values of $\frac{\text{width}}{\text{thickness}}$ of 7 and 12 the percentage elongation is nearly constant. The maximum increase in elongation is about 50 per cent. of the elongation on the narrowest test-bar.

(ii) Elongation on a variable gauge length (where gauge length is equal to constant $\times \sqrt{\text{cross-sectional area}}$) is very nearly constant. The maximum variation is only about 8 per cent. of the elongation with the bar of smallest cross section.

A long series of tests by Thos. Firth & Sons [4] demonstrates the fact that, whereas metals such as copper and soft brass give large elongations when tested in thin sheets, annealed sheet steel gives hardly any elongation though the metal from which it is prepared has a normal elongation when tests are made on the standard form of cylindrical test-piece.

§ 56. **The Elongation Equation.**—A. *Variation with Gauge Length.*—The elongation of a test-bar is made up of two parts :—

(i) The general extension occurring before the maximum load is reached and which is approximately uniformly distributed along the bar and therefore proportional to the gauge length.

TABLE IX.

GORDON AND GULLIVER'S RESULTS ON FLAT TEST-BARS.

Width in Inches.	Width / Thickness	Per Cent. Elongation on Gauge Length $= 11{\cdot}3\sqrt{A}$.		Per Cent. Elongation on Gauge Length = 8 Ins.		Yield Stress in Tons per Sq. In.	Ultimate Stress in Tons per Sq. In.
		Gap Included.	Gap not Included.	Gap Included.	Gap not Included.		
½	1·76	28·2	27·6	22·6	22·3	18·2	25·3
1	3·81	28·8	28·1	26·1	25·7	18·3	25·3
1½	5·64	30·2	29·2	29·0	28·1	18·3	25·4
2	7·57	30·4	29·5	30·4	29·5	18·1	25·4
2½	9·57	29·4	28·5	31·6	29·6	18·1	25·5
3	11·14	28·7	27·3	31·1	29·3	18·0	25·4
3½	13·32	28·2	27·3	31·9	30·7	18·0	25·7
4	15·39	29·7	28·7	33·9	32·5	18·2	25·9

(ii) A local extension independent of the gauge length occurring after the maximum load has been reached.

If L = the gauge length

e = the total extension

then $e = a + bL$ where a and b are constants, the former for the local extension and the latter for the general extension.

The percentage extension

$$= 100 \times \frac{e}{L} = \frac{100}{L}(a + bL) = 100\left(\frac{a}{L} + b\right) \quad \text{(equation 1)}$$

i.e. the percentage extension for a given sectional area decreases as L is increased.

B. *Variation with Cross Section.*—Only the local extension is affected by the cross-sectional dimensions of the test-piece, i.e. the term "a" in equation (1).

Since the local contraction is proportional to the linear dimensions of the cross section and the extension is not affected by the form of the cross section, $a = c\sqrt{A}$ (equation 2).

where A = the cross-sectional area

c = a constant

i.e. for dissimilar test-bars

$$\text{elongation per cent.} = 100\frac{e}{L} = 100\left(\frac{c\sqrt{A}}{L} + b\right) \text{(equation 3).}$$

This formula is true, provided—

(*a*) The gauge points are not too close to the enlarged ends of the test-piece.

(*b*) The length L is not so short as to fall within the area affected by the local contraction.

Equation 3 is in agreement with Barba's Law for similar test-pieces that, when similarity is maintained, the percentage elongation is constant because in that case $\frac{\sqrt{A}}{L}$ and therefore *e* becomes constant.

Unwin [1] gives the following method of least squares for calculating the values of *b* and *c* in the elongation equation from a series of observations :—

The elongation equation is—

$$e \text{ per cent.} = \frac{c\sqrt{A}}{L} + b.$$

For simplicity, let $\frac{\sqrt{A}}{L} = a$, and suppose the elongations have been observed for *n* gauge lengths. Then the most probable values of the constants are given by the equations—

$$c = \frac{n\Sigma ea - \Sigma e\Sigma a}{n\Sigma a^2 - (\Sigma a)^2}, \quad b = \frac{\Sigma e\Sigma a^2 - \Sigma ea\Sigma a}{n\Sigma a^2 - (\Sigma a)^2}.$$

Applying these results to bar 84 (Table IV) whose diameter = 1·000 inch and area = 0·7854 square inch and per cent. elongation on

$$\left.\begin{array}{l} 3'' = 41\cdot0 \\ 4'' = 36\cdot5 \\ 5'' = 34\cdot0 \\ 6'' = 31\cdot8 \\ 7'' = 30\cdot1 \\ 8'' = 28\cdot8 \end{array}\right\} \text{ we have } \sqrt{A} = 0\cdot8863 \text{ and } n = 6.$$

L.	$\frac{\sqrt{A}}{L} = a.$	*e.*	*ae.*	a^2.
3	·2954	41·0	12·110	·08724
4	·2216	36·5	8·088	·04910
5	·1773	34·0	6·027	·03143
6	·1477	31·8	4·696	·02181
7	·1266	30·1	3·810	·01603
8	·1108	28·8	3·191	·01227
	$\Sigma = 1\cdot0794$	202·2	37·922	·21798
	$(\Sigma a)^2 = 1\cdot165$			

$$c = \frac{(6 \times 37{\cdot}92) - (202{\cdot}2 \times 1{\cdot}0794)}{(6 \times {\cdot}2179) - 1{\cdot}165} = 65{\cdot}5$$

$$b = \frac{(202{\cdot}2 \times {\cdot}2179) - (37{\cdot}92 \times 1{\cdot}079)}{(6 \times {\cdot}2179) - 1{\cdot}165} = 22{\cdot}1$$

and therefore the elongation equation for this bar of material is

$$e \text{ per cent.} = \frac{65{\cdot}5\sqrt{A}}{L} + 22{\cdot}1.$$

§ 57. **Contraction of Area at Fracture.**—If "a" is the initial area of the test-bar and "A" the area at the point of fracture, then the reduction of area is equal to $a - A$ and the percentage reduction of area $= \left(\frac{a - A}{a}\right) \times 100$.

If the material is perfectly plastic the percentage contraction of area is equal to the percentage elongation where the latter is calculated on the final length of the test-bar,

i.e. $$\left(\frac{a - A}{a}\right) \times 100 = \left(\frac{L_2 - L_1}{L_2}\right) \times 100$$

(L_1 and L_2 are the initial and final lengths respectively).

The proof of this is as follows :—

The volume of the test-piece is assumed to be constant,

therefore $$L_1 \times a = L_2 \times A$$

or $$\frac{A}{a} = \frac{L_1}{L_2}$$

subtracting each from unity we have

$$1 - \frac{A}{a} = 1 - \frac{L_1}{L_2}$$

or $$\frac{a - A}{a} = \frac{L_2 - L_1}{L_2}.$$

The agreement between elongation and contraction of area is only for the short part of the specimen where there is plastic deformation and it does not apply to greater lengths.

Prof. Elliot [5] has given a method of calculating the constants, b and c, of the elongation equation $\left(e = \frac{c\sqrt{A}}{L} + b\right)$ when the elongation is only known on one gauge length together with the contraction of area of the test-bar. The method depends upon the assumption of a value for the original length of the contracted

region. Taking this as $m\sqrt{A}$ Elliot found that "m" varied from 0·9 to 2·0 and adopting the value of 1·37 he obtained very fair agreement with results previously published by Unwin.[1]

REFERENCES FOR CHAPTER VI.

[1] Unwin, "Tensile Tests of Mild Steel," "Inst. Civ. Eng. Proc.," Vol. CLV, 1904, p. 175.
[2] Barba's Law, see Unwin as above, p. 179.
[3] Gordon and Gulliver, "Roy. Soc. Edin. Trans.," Vol. XLVIII.
[4] Jenkin, C. F., "Report on Materials of Construction used in Aircraft and Aircraft Engines," p. 7.
[5] Elliot, "The Relation of the Constants of the Elongation Equation to Contraction of Area," "Inst. Civ. Eng. Proc.," Vol. CLVIII, 1904, p. 390.

CHAPTER VII.

PROCEDURE IN ORDINARY COMMERCIAL TESTING.

§ 58. COMMERCIAL testing is undertaken primarily to ascertain if the material is of the quality required by a specification. These inspection or reception tests have to be made quickly and are principally directed to giving indications of the strength and ductility of the material.

§ 59. **Preparation and Selection of Test-pieces.**—The test-pieces must be selected so as to give a reliable indication of the material as a whole. Sampling is inherently imperfect and is therefore apt to cause difficulties. Samples should always be taken and stamped in the presence of an inspector acting on behalf of the purchaser and there should be safeguards to avoid heat treatment or other manipulation after selection.

The number of tests should be specified and, in order to cover errors which are likely to arise, limits should be allowed on the test results and provision made for re-test if necessary. A usual clause is that, should the test-piece fail to conform to the specification, the contractor shall have the opportunity of two further samples being selected by the inspector and tested at the manufacturer's expense. Both of these samples must pass in order for the consignment to be accepted.

Test-pieces, if to be taken from a sample, such as a tyre, axle, crankshaft, etc., should be cut out by cold sawing or drilling and subsequently prepared by milling, turning or planing. Should shearing be unavoidable, care must be taken to ensure that the material is not bent and that the sheared edges are entirely removed before testing. Cutting by oxyacetylene blow-pipe should not be allowed as it alters the structure of the material for from 2 to 3 inches from the cut.

Iron or steel plates are usually tested both in the direction of rolling and across it and with cast iron special bars are made from each cast for transverse test. For some materials special bars form part of the casting and are afterwards cut off for testing,

but it is usual to specify the position of these bars and whether they are to be sand or chill castings.

For special tests some form of heat treatment, such as normalising, annealing or tempering, may be required.

Annealing means reheating followed by slow cooling. Its purposes may be either, to remove internal stresses and induce softness or to refine the crystalline structure. In the latter case the temperature used must exceed the upper critical range but not more than by 50° C.

Normalising means heating a steel (however previously treated) to a temperature exceeding its upper critical range (but not more than by 50° C.) and allowing it to cool freely in air. It is desirable that the steel should soak at the required temperature for about fifteen minutes.

Hardening means heating a steel to its normalising temperature and cooling more or less rapidly in a suitable medium, such as water, air, or oil.

Tempering is to reduce the hardness and increase the toughness and is carried out by heating the steel (however previously hardened) to a temperature not exceeding its carbon change point.

§ 60. **Marking Test-pieces.**—It is essential that, in the test-house, a method of numbering test-pieces should be used by which the full history of any specimen can always be traced from the number on the test-piece. The method adopted will depend, primarily, upon the class of work undertaken. Where the amount of work is small and the tests principally of one kind, such as transverse tests on cast iron in a foundry, the test-pieces can be numbered numerically, This method, however, is apt to lead to confusion where more than one test is required from the same sample. For work of a very varied character—including research, investigatory and commercial testing—the authors have found the following system to work satisfactorily.

Each sample or batch of samples is given a serial letter. Starting from A, the twenty-sixth sample will be lettered Z. Two letters are then used, viz. AA to AZ, BA to BZ, etc., until ZZ is reached, when combinations of three letters are employed. By using letters instead of figures for the serial "Number" over seventeen times as many samples can be tested without exceeding three stamp marks for the sample number. It is obviously an advantage to keep the marking on the test-pieces as small as possible.

If the sample consists of more than one piece, each piece is

figured consecutively in addition to the sample number and test-pieces cut from the piece are again lettered in order. Particulars of the sample, together with the number of the test-book in which the results are recorded, are entered against the sample number in a book kept for that purpose.

Thus, for example, two pieces of plate from a boiler are received for a series of tests. Particulars are entered in the sample book against the next sample serial letter, say BMT. The two pieces of plate are then numbered BMT1 and BMT2 respectively. If three test-pieces are to be cut from each plate, these are numbered BMT1A, BMT1B, BMT1C, and BMT2A, BMT2B, BMT2C.

At some future time a broken test-piece numbered BMT2B may require identification. The history of that test-piece is at once indicated from its number, and particulars of the test results are found by consulting the test-book whose number is entered against BMT in the sample book.

§ 61. **Tension Tests.**—The data ordinarily observed in a tensile test for reception purposes is:—

Yield load.
Maximum load.
Elongation after fracture.
Contraction of area at fracture.

§ 62. **Yield Point and Elastic Limit.**—There seems to be confusion, very often, as to exactly what is meant by the elastic and yield points. It is a common practice for the elastic limit to be specified when what is actually required is the yield point. The actual elastic limit can only be obtained by the use of delicate strain measuring instruments. The term elastic limit itself is ambiguous and it is better not to use it; what is meant is the point at which the limit is reached of proportionality between the load applied and the extension measured. Modern practice is to call this the limit of proportionality. The limit found in this way is a "primitive" limit, it depends, not only on the material itself, but on the treatment which that material has previously received.

The yield point is slightly higher than the limit of proportionality and is the point at which there is an increase in the extension without a corresponding increase in the load. This point occurs in wrought iron or mild or medium carbon steel and is usually well marked. With hard steel, bronze and most alloys

it is non-existent, the rate of extension with load increasing after the limit of proportionality without any sudden jump.

For commercial testing the yield stress is the load per unit area at which there is a sudden visible increase in the extension between the gauge marks on the test-piece, or it may be taken as the stress at which the beam or indicator distinctly drops when the load is applied at a uniform rate.

The authors prefer to record that "there is no yield point" in cases where these conditions are not observed. Many specifications require an arbitrary yield point and it is sometimes taken as the point at which the test-piece extends approximately $\frac{1}{200}$ of the gauge length. This practical definition is seen to be quite unsatisfactory when it is remembered that, with a stress of about 67 tons per square inch, steel has an elastic extension of $\frac{1}{200}$ of the gauge length. It is better to eliminate the yield point and substitute a proof stress (see § 63), and this is now being done in many specifications.

Johnson [1] proposes that "in view of the difficulty of determining the true elastic limit an apparent elastic limit be taken as the point on the stress-strain diagram at which the rate of deformation is 50 per cent. greater than it is at the origin. Under this definition, the apparent elastic limit would practically correspond to the yield point in materials having such a point and would give a reasonable value for such materials as cast iron, or hard steel, for which this diagram shows a very gradual curvature away from the straight line. Such a criterion has much merit and would accomplish the following results :—

"1. It would always fix one and the same well defined point.

"2. This point would always correspond to so small a permanent deformation as to be, for many practical purposes, the true elastic limit.

"3. It is equally applicable to all kinds of tests, whether on specimens or on finished members or structures, where deformations of any kind can be correctly measured.

"While the 50 per cent. increase in the rate of deformation is purely arbitrary, it is not large enough to fix a point having an appreciable permanent set, but it is large enough to fix a well defined point on the stress-strain diagram."

Unwin,[2] however, says that "such a point has no significance," also, "that the attempt sometimes made to define arbitrarily a yield point for materials which have no distinct yield point and, often as manufactured, no elastic limit either, appears to him to be useless and misleading".

It is convenient, where a considerable amount of testing has to be done on the same size of test-piece, to use a simplified extension measurer applied to the test-piece instead of dividers. G. H. Roberts [3] describes and illustrates an instrument of this kind in which the extension of the test-piece is communicated to the pointer on a dial. One division on the dial indicates a movement between the jaws of 0·001 inch. The yield point is seen quite definitely if it occurs, or the load for an extension of 1/200 of the gauge length can be also noted with fair accuracy.

Capp's [4] multiplying dividers answer the same purpose. They are illustrated in Fig. 90 and consist of two arms (A and B) so pivoted that the motion of the points (C and D) in which the short arms terminate is multiplied about ten times at the scale (S) and pointer forming the ends of the long arms. To use the instrument the points of the dividers are placed in the centre punch marks on the test-piece and held firmly in place when the load is applied. The pointer moves across the scale slowly until

FIG. 90.—Capp's multiplying dividers.

the yield point when a sudden and marked increase in the rate is observed.

§ 63. **The Proof Stress.**—In view of the irregular use of the yield stress it is now becoming common, as mentioned in § 62, to substitute a proof stress in modern specifications.

The intensity of stress specified is to be applied to the material for fifteen seconds and when removed must not have produced a permanent set of more than ½ per cent. between the gauge points. The beam of the testing machine is to remain floating while the load is applied.

OPRS (Fig. 91) represents the load elongation curve of a material having no definite yield point. The limit of proportionality is at P, and O*r* represents an elongation of ½ per cent. between the gauge points. If *r*R is drawn parallel to the elastic line OP, cutting the curve in R, then with a load OT (corresponding to R) the test-piece has a permanent set of O*r* (½ per cent.). Should the proof stress (say ON) give a point M on the curve between O and R the permanent set (O*m*) is then less than O*r*, i.e. less than ½ per cent., and the material passes the specification.

§ 64. **The Maximum Load.**—An autographic stress-strain diagram shows that, with a test-bar which "necks" before fracture, the actual load necessary to break the test-piece at the neck is less than the maximum load on the bar before the reduction of area takes place. Nevertheless, the stress obtained by dividing the breaking load by the reduced area is greater than the stress obtained by dividing the maximum load by the original area of the bar, which is the figure required by specifications.

The terms breaking stress, maximum stress, and ultimate stress are applied indiscriminately to indicate the maximum load divided by the original area which is desired by specifications. It is obviously not the maximum stress, although it is calculated

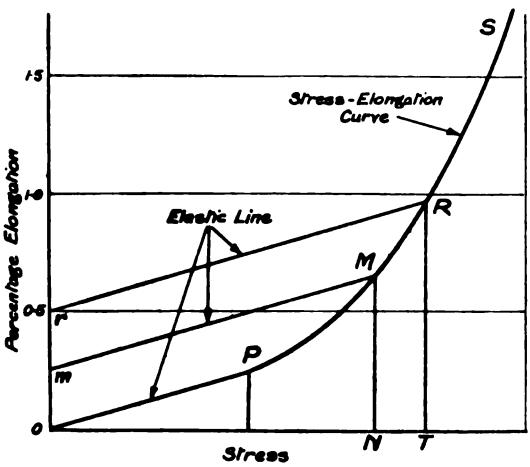


FIG. 91.—Curve illustrating the proof stress.

from the maximum load. As the term breaking stress is also liable to be misunderstood the authors prefer to call it the **ultimate stress.**

§ 65. **Percentage Elongation and Contraction of Area.**—In specifications the elongation and contraction of area are required in order to obtain a measure of the ductility of the material. Both are empirical values and the former, as has been shown in § 56, is dependent on the cross section of the test-bar and the gauge length. It has been suggested that the percentage general extension instead of the percentage total extension should be adopted, as this is independent of the form of test-bar. It would, however, complicate the calculation of the results and,

owing to the general adoption of the other method of expression, would doubtlessly cause considerable confusion.

The general extension, if it is required, is obtained either:—

(*a*) From an autographic diagram as the extension at maximum load, i.e. before the necking of the test-piece, or

(*b*) from the measurement of the elongation on two gauge lengths on the same test-piece.

Thus if e_1 = elongation on gauge length L_1
e_2 = elongation on gauge length L_2
a = total local extension
B = the general extension per unit length

then $e_1 = BL_1 + a$
$e_2 = BL_2 + a$

and the general extension per unit length = $B = \frac{e_2 - e_1}{L_2 - L_1}$

and the total local extension = $a = \frac{e_1L_2 - e_2L_1}{L_2 - L_1}$

e.g. with a 30-ton steel, diameter = 1·000 inch.

Extension on 8 inches = 2·37 inches (29·6 per cent.).

Extension on 3 inches = 1·32 inches (44·0 per cent.).

$$B = \frac{2{\cdot}37 - 1{\cdot}32}{8 - 3} = \frac{1{\cdot}05}{5} = 0{\cdot}21$$

$$a = \frac{(1{\cdot}32 \times 8) - (2{\cdot}37 \times 3)}{8 - 3} = \frac{3{\cdot}45}{5} = 0{\cdot}69$$

i.e. general extension = B = 21 per cent.

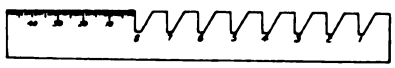
§ 66. **Measuring the Extension.**—The gauge length in ordinary commercial testing is marked on the bar before it is tested, by means of either a double centre punch or a laying off and per cent. gauge (both shown in Fig. 92). It is, however, nearly as convenient and almost as quick to use a pair of dividers set to the correct gauge length. It is necessary to have a V block to support the test-piece during the marking-off process.

As long as the fracture is not less than a length equal to the square root of the area inside the gauge mark the measure of the elongation is usually accepted as satisfactory (i.e. 0·5 inch for a test-piece of 0·25 square inch area or 0·7 inch for a test-piece of 0·5 square inch area).

Sometimes it is specified that "should a tensile test-piece break outside the middle half of its gauge length the test may, at the contractor's option, be discarded and another tensile test

shall be made from the same bar, billet, sheet, forging or drop forging". The middle half is defined as shown in Fig. 93.

§ 67. **Method of Reporting Results.**—It is desirable that the results should be reported in such a manner that the information can be assimilated as easily as possible. It adds greatly to the facility with which the results can be compared and scrutinised



Laying off and percent gauge

Double centre punch

FIG. 92.

if the form of report is always in the same style. The following points are also worth consideration.

(1) The report should contain as far as possible the actual observations.

(2) The heads of information which are purely observational and those which have been reduced by calculation should be

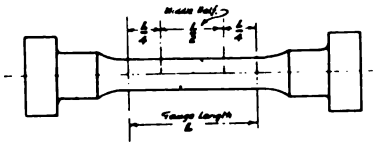


FIG. 93.—Diagram showing meaning of "middle half" of the test-piece.

kept separate. It is convenient to have the latter on the right hand side of the form.

A typical form for tensile tests is given in Table X, together with the results of a few tests. It is seen that the information which is ultimately required is given in the last five columns.

§ 68. **Example of Test Record and Calculation of Results.**—

TENSILE TEST ON STEEL FOR H. C. L. & CO., LTD., MATERIAL RECEIVED, JULY 1ST, 1921.

	(1)	(2)	(3)
Test No.	1415		
Identification marks	HLIE		
Gauge length	2 ins.		
Dimensions of test-piece	0·565 in. diam.		
Cross-sectional area of test-piece	0·2507 sq. in.		
Yield load	6·40 tons	6·40/0·2507	
Yield stress			25·5 tons per sq. in.
Maximum load	9·17 tons	9·17/0·2507	
Ultimate stress			36·66 tons per sq. in.
Elongation	0·62 in.	(0·62/2) x 100	31·0 per cent.
Distance of fracture from gauge mark	0·65 in.		
Dimensions at fracture	0·330 in. diam.		
Area at fracture	0·0855 sq. in.	$\frac{\cdot2507 - \cdot0855}{\cdot2507}$	
Reduction of area at fracture			65·9 per cent.
Remarks			

Ref. RGB/HL, July 4th, 1921.

It will be noted that, with the exception of the area, the observed values are given in column (1) and the calculated values in column (3). This method simplifies the typing of the report as given in Table X.

§ 69. **Forms of Tensile Test-bars.**—It is shown by experiment that the form of the tensile test-piece has an influence on both the elongation and the strength.

The elongation with ordinary test-bars is measured on a gauge length of uniform section. The effect of the enlarged ends is to reduce the local drawing out of the material. The parallel part of the test-piece is therefore always made somewhat greater than that on which the elongation is measured. If the length of the parallel section is reduced so as to form an abrupt change in cross section of the bar tested under tension, a concentration of stress is caused at the bottom of the groove or notch which is thus formed, while the shoulders formed by the groove prevent free elongation of the metal.

In a material which extends very little, an abrupt change of section will lower the breaking load while, with a ductile material the suppression of the local drawing out gives an increased tensile stress.

The influence of the gauge length on the percentage elongation has been discussed in § 54.

TABLE X.

REPORT OF TENSILE TESTS CARRIED OUT ON "VARIOUS HEAT-TREATED STEELS" SUPPLIED BY MESSRS. H. C. L. & CO. LTD., FOR WHOM THE TESTS WERE MADE.

Test Number.	Identification Marks.	Original Dimensions.			Yield Load in Tons.	Maximum Load in Tons.	Dimensions at Fracture.				Yield Stress, Tons/Sq. In.	Ultimate Stress, Tons/Sq. In.	Elongation, Per Cent.	Reduction of Area, Per Cent.	Remarks.
		Gauge Length in Inches.	Dimensions in Inches.	Area in Sq. In.			Extension in Inches.	Distance of Fracture from Gauge Mark.	Dimensions in Inches.	Area in Sq. In.					
1415	HL1E	2	·565	·2507	6·40	9·19	0·62	0·65	0·330	0·0855	25·5	36·66	31·0	65·9	
1416	GA1E	2	·564	·2498	5·90	9·65	0·61	1·00	0·345	0·0935	23·6	38·63	30·5	62·6	
1417	HL2E	2	·564	·2498	9·10	15 97	0·52	1·10	0·395	0·1225	36·4	63·94	26·0	51·0	
1418	GA2E	2	·564	·2498	9·50	17·88	0·40	0·70	0·420	0·1385	38·0	71·58	20·0	44·6	
1419	HL3E	2	·565	·2507	9·30	14·25	0·47	1·00	0·415	0·1353	37·1	56·85	23·5	46·0	

Order No. *Date*
Reference *Tested by* *Director.*

On account of the considerations stated above it is essential that definite types of specimen should be specified for commercial tests in which the results of the tests decide whether the material is to be accepted.

As a result of the work of Barba, the French Commission recommends the adoption of the relation

$$L^2 = 66{\cdot}67A$$
or $L = 7{\cdot}2D$ for circular specimens
where L = the gauge length.
A = area of cross section
D = diameter of the test-bar.

The German Commission recommends the use of the relation

$$L = 11{\cdot}3\sqrt{A}$$
or $L = 10D$ for circular specimens.

Thus while, with a test-piece 10 mm. diameter, a gauge length of 72 mm. is recommended in France a length of 100 mm. is adopted in Germany.

Owing to the practical difficulties in the way of adopting a varying gauge length for different cross sections of test-piece cut from plates and other rolled sections, fixed standards for cylindrical and flat specimens have been prescribed by the American Society for Testing Materials (A.S.T.M.) and the British Engineering Standards Association (B.E.S.A.).

The sizes selected by the B.E.S.A. (Report No. 18, see Appendix) are given in Fig. 94. Those adopted for cylindrical test-bars of forgings (Fig. 94) approximately satisfy the law of similarity where

$$L = 4\sqrt{A}$$

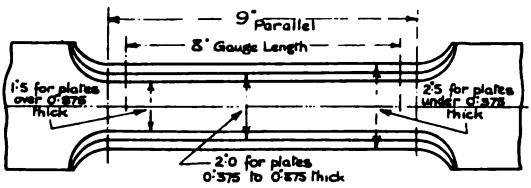
viz :—

Diameter. Ins.	Area in Sq. Ins.	Gauge Length. Ins.
0·564	0·250	2
0·798	0·500	3
0·977	0·750	3½

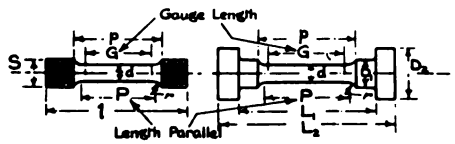
For plates, both 10-inch and 8-inch gauge lengths were in use before the B.E.S.A. standard was published. A standard width of 2 inches was used for convenience in milling, this gave a cross-sectional area varying with different thicknesses of plate

and thus disregarded the effect of the cross-sectional area on the percentage elongation.

In order to overcome this difficulty the B.E.S.A. standardised



Standard Sizes of Test Pieces for Plates



	d	G	P	p	l	S	L_1	L_2	D_1	D_2
*	0·877	3·50	4·00	5	8	1·5 B.S.N	6·25	8	1·25	1·75
*	0·798	3·00	3·375	4	6·5	1·25 B.S.N	5·25	6·5	1·0	1·5
*	0·564	2·00	2·25	3	4·5	0·75 B.S.F	4·25	5·25	0·75	1·25
	0·358	1·25	1·50	2	3	0·50 B.S.F	-	-	-	-
	0·125	0·443	0·625	0·875	1·5	"0" B.A.	-	-	-	-

Radius r should be as large as is consistent with other dimensions

* These are B.E.S.A. Test Pieces.

Standard Forms of Cylindrical Test Bars

FIG. 94.—Standard sizes of test-bars.

test-bars having a fixed gauge length of 8 inches and a width varying with the thickness of the plate. In order to lessen the cost of production, three widths only were chosen, viz :—

Thickness of Plate. Ins.	Width of Test-bar. Ins.	Gauge Length. Ins.
Under $\frac{3}{8}$	$2\frac{1}{2}$	8
$\frac{3}{8}$ to $\frac{7}{8}$	2	8
Over $\frac{7}{8}$	$1\frac{1}{2}$	8

If the test-piece is free from abrupt changes of section, the ultimate stress is independent of the cross-sectional area of the

bar. This is seen from the results on cylindrical specimens given in Table VI, and from those on plate specimens in Tables VII and IX.

§ 70. **Tensile Test Fractures.**—The form of fracture of a test-bar is influenced by the structure of the material of which the bar is made and the system of stress distribution in the bar. With a uniform material in which the properties in all directions and at all points are identical the stress distribution depends on the shape of the test-piece and the loads applied, and the forms of fracture are ideal.

Different forms of ideal surface of fracture are obtained with materials of different properties.

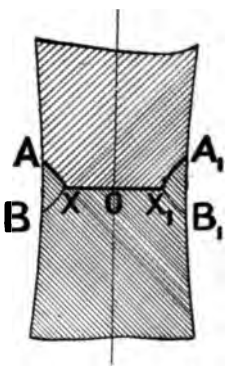


FIG. 95.—Standard form of tensile fracture for a round bar.

No material is perfectly uniform, so that the ideal form of fracture is not obtained, but fractures of regular types are constantly observed, especially with materials of fine structure which have had some amount of "work" applied to them.

If the load is axial the boundary of the crack is symmetrical about the longitudinal axis of the test-bar and commences either on the axis or all round a closed curve symmetrical about that axis.

The standard form of fracture is given in Fig. 95 and takes the form, in a round bar, of a truncated cone with the slant surfaces curved in outline. The flat central part (XOX_1) of the cupped fracture is called the base and the fracture is completed by a lipped surface shown in section by AX and A_1X_1.

The test-bar is first broken along the basal surface XOX_1, and with an absolutely uniform material the crack then extends along both XA and XB. A small irregularity causes the crack to develop more rapidly along one of these surfaces with the result that it ultimately breaks either at A or B and the usual form of fracture is obtained. A photograph of a typical example of a symmetrical fracture of this kind is given in Fig. 96.

The amount of the basal or flat surface (XOX_1) varies with different materials, the extremes being either wholly flat or wholly curved, both forms being met with in practice.

A slight variation of the standard symmetrical fracture is the form which is most commonly met. The lip of the cup is not complete and parts of the curved portion of the surface of fracture

FIG. 96.

FIG. 97.

Symmetrical fracture.

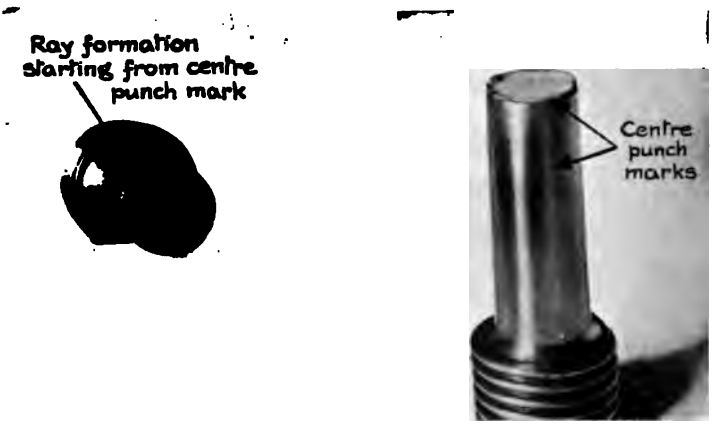


FIG. 98.—Fracture starting from a centre punch mark.

[*To face p.* 119.

are found on both sides of the basal surface XOX_1. Such a fracture shown in Fig. 97 does not indicate any want of symmetry of the load with respect to the axis of the test-piece but merely shows that the path of least resistance to the propagation of the crack was not entirely along the curve on one side of the flat surface.

Fractures which do not follow the types mentioned above are asymmetric and indicate that—

(*a*) The loading has not been axial.

(*b*) There is a lack of homogeneity in the material, or

(*c*) Defective loading has been combined with want of uniformity in the material, such as a flaw.

With a brittle material the fracture is wholly flat even though it is asymmetric. The surface is not, however, entirely smooth, and with a material in which the structure is not too coarse small channels can be seen radiating from the point at which fracture commenced. An asymmetric fracture therefore has rays which do not originate on the axis of the bar. Fig. 98 shows ray formation starting from a centre punch mark on the bar. The point at which fracture commences is readily seen in a rectangular bar; after the bar has been broken and the pieces are placed together it is noticeable that the outer edges touch and leave a gap which is greatest at the centre (see Fig. 89). This is found on each side of the bar but is more marked on the wide sides than on the narrow ones. It is a clear indication that after the metal fractures near the centre of the bar, the metal near the edge continues to stretch.

§ 71. **Enlarged Ends of Test-pieces.**—The design of the enlarged ends of test-pieces requires care in order to be sure of satisfactory results. It has already been stated that axial alignment of the test-piece is necessary for accurate work and that this is best attained by the use of spherically seated holders.

For brittle materials it is essential that the transition from the parallel part of the test-piece to the enlarged ends is gradual, and that any part of the enlarged ends which is screwed, or otherwise has a sharp corner, is sufficiently large to prevent fracture at that place. Forms of ends for turned test-pieces of cast materials are given in Fig. 99.

Test-pieces may be tapered inside the gauge length towards the centre, to an amount not exceeding 0·003 inch for turned test-pieces and 0·01 inch for sheets or plates, in order to induce fracture near the centre of the gauge length. If this is done the

middle half of the gauge length of the test-piece should be parallel.

§ 72. **Compression Tests on Metals.**—With the more plastic metals there is no well-defined point of breakdown under compression and it is usual to record the compressive strength at a given unit of deformation. The values which are obtained in this way are only comparative and do not give results which can be used as a basis for calculating sizes of structures.

With brittle materials the ultimate stress can be obtained with precision and the results are of value for calculating sizes of compression members.

For metals the test-piece is usually a cylinder whose ratio of length to diameter is two.

It is important, especially with brittle materials, that a spherical seated shackle should be provided in order to adjust for

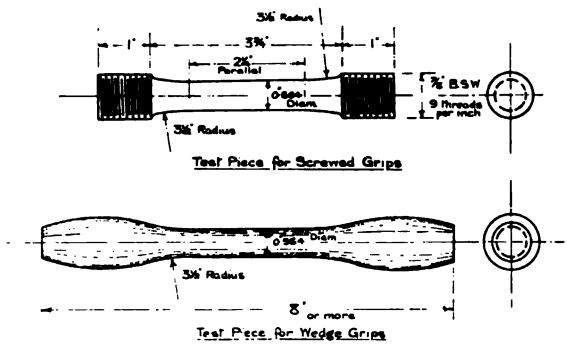


FIG. 99.—Forms of tensile test-pieces for brittle materials.

inaccuracy of the parallelism of the shackles. Care should be exercised to ensure that the pressure is applied axially. Shackles for this purpose are described in § 48.

§ 73. **Quality Factor.**—Various empirical means of estimating the quality of the material from the results of the tensile test have been suggested. They combine the tensile strength with either the percentage of elongation or percentage contraction of area at fracture. The only factor which has been used to any large extent in this country is a modification of one suggested by Wöhler.

Wöhler's quality factor $= p + c$

and the modified factor $= p + e$

where p = tensile strength

e = per cent. elongation

c = per cent. contraction of area.

A quality factor must be used with care, bearing in mind the use to which the material is to be put.

§ 74. **Bend Tests.**—A rough workshop test of the ductility of metals is given by the bend tests of various types which are now in common use. The test is made by bending a piece of the material either by steady pressure or hammering, the former giving the more concordant results, until an angle of 180° is reached or previous rupture takes place. In the latter case the angle is noted at which fracture occurs on the outside of the bend. A large amount of experimental work has been carried out by Mr. Bernard Firth [5] but the test has not been so carefully standardised as the tensile test.

The test is also used for ascertaining the effect of punching and drilling on the ductility, by using perforated plate specimens with the hole in the centre of the plate. The diameter of the hole, as recommended by Martens, should be twice the thickness of the plate and the width of the specimen five times its thickness.

§ 75. **Kinds of Bend Test.**—The principal types of bend test in use are—

(*a*) Cold bend test (as received).
(*b*) Cold bend test (annealed).
(*c*) Quench bend test or temper bend test.
(*d*) Hot bend test.
(*e*) Nick bend test.

(*a*) **Cold Bend Test.**—This is the type which is most commonly used and is carried out at normal temperature. To test the ductility at low temperature the test-pieces are sometimes cooled artificially.

(*b*) **Annealed Bend Test.**—For the annealed bend test the material is, previously to bending, reheated to a temperature exceeding its upper critical range followed by slow cooling. The steel is usually very bad if it cracks after annealing.

(*c*) **The Quench Bend Test** is used for determining the effect of alternations of high and low temperature on the ductility on such materials as boiler-rivet steel and stay-bolt iron. Before applying the bend test the material is heated to blood-red and plunged into water at a temperature of 80° F. The colour is judged indoors in the shade.

(*d*) **The Hot Bending Test** is specified to detect red shortness or high sulphur content. The material is bent while at a temperature of about 950 to 1000° C.

(*e*) **The Nicked Bend Test** is intended to show whether the material has a crystalline or fibrous structure. The test-piece is

nicked all round before bending, with a tool having a cutting angle of 60°. The depth of the notch is 8-16 per cent. of the diameter of the test-piece. The test-piece should be placed so that the bend occurs with the minimum depth.

§ 76. **Forms of Specimens for Bend Tests and Methods of Testing.**—Rods are usually tested without machining. Plates should be planed at the sides after shearing and the corners rounded with a file, otherwise cracks may start at the corners due to the shearing process having weakened the metal. With plates

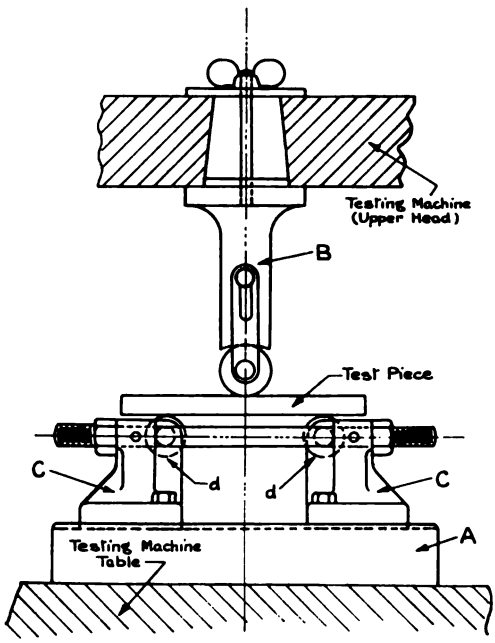


FIG. 100.—Cold bending apparatus.

over 1 inch thick it is especially important that this precaution should be taken.

It is usual to bend bars, unless otherwise specified, round a mandrel of a radius equal to the diameter or thickness of the bar.

For axles and steel forgings the British Engineering Standards Association (Report No. 24, see Appendix) specify a test-piece 9 inches long and $1\frac{1}{4}$ inch square with a $\frac{1}{16}$-inch radius at the edges. The radius of the bending tool is also specified and varies from $1\frac{1}{4}$ inch for material having an ultimate stress of 40

to 45 tons per square inch to $\frac{3}{4}$ inch for material of 25 to 32 tons per square inch, ultimate stress.

Steel castings are usually only required to be bent through 90° without fracture; the test-piece is 9 inches long and 1 inch diameter and the radius of the bending tool is $1\frac{1}{4}$ inch.

A cold bending apparatus is shown in Fig. 100 in which a steady pressure is applied during the test. The lower plate (A) rests on the table of the testing machine while the upper tool (B) is held in place in the pulling head by wing nuts and plate. The brackets (CC) are spaced sufficiently apart to allow the upper tool and twice the thickness of the specimen to easily pass between

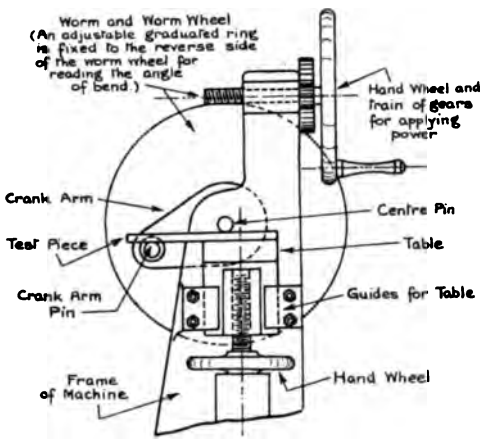

Worm and Worm Wheel
(An adjustable graduated ring is fixed to the reverse side of the worm wheel for reading the angle of bend.)
Hand Wheel and train of gears for applying power
Crank Arm
Centre Pin
Test Piece
Table
Crank Arm Pin
Guides for Table
Frame of Machine
Hand Wheel

FIG. 101.—Bend testing machine (hand power for specimens up to 1 inch square).

the lower rollers (*dd*). The rollers can be changed so as to adapt the apparatus for either round, square, or twisted bars.

Where a large number of tests have to be carried out, and the testing machine or press cannot be spared, it is usual to have a special machine used exclusively for bend tests. A machine for specimens up to 1 inch square is shown in Fig. 101.

The correct size of centre pin is first put in the machine, the crank arm is next rotated until the crank arm pin is below the level of the test-piece and then the table is adjusted by means of the small hand-wheel until the top of the specimen rests against the centre pin which should be at about the centre of the specimen. The graduated ring is set to zero and power is applied to the crank arm which revolves until the test-piece ruptures or the required angle of bend, read off on the graduated ring, is reached.

A fatigue test is sometimes used as an alternative to the bend test. The test-piece is placed on bearings with a span of 6 inches and must stand without fracture 20 blows from a weight (of 1120 lbs.) having a rounded end of 1¼ inch radius and falling 6 inches. The test-piece is to be reversed after the first and every alternate blow. The height of fall after the 20 blows is increased to 12 inches and the test continued until fracture occurs.

Bend tests are now often replaced by single blow notched bar tests (see § 193-205), but these require special testing plant.

§ 77. **Tests for Rivets.**—Rivets are usually subjected to a bend test and a flattening test. For the bend test they are hammered cold without cracking until the two parts of the shank touch (Fig. 102*a*), and for the flattening test the heads are hammered while the rivet is hot and must flatten, without crack-

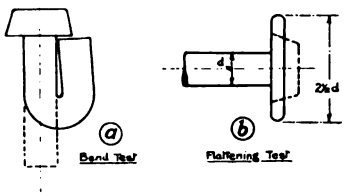


FIG. 102.—Tests on rivets.

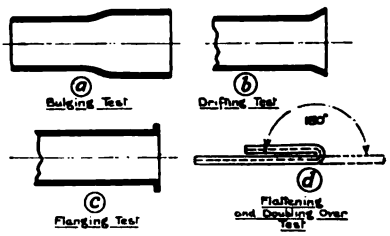


FIG. 103.—Tests for copper and brass tubes.

ing of the edge, to a diameter which is two and a half times that of the shank (Fig. 102*b*).

§ 78. **Bulging, Drifting, Flanging and Flattening Tests for Copper and Brass Tubes.**—It is usually specified that brass and copper tubes shall stand a certain percentage increase in the diameter (25 per cent. is usual) without crack or flaw when subjected to bulging (Fig. 103*a*), drifting (Fig. 103*b*), or flanging (Fig. 103*c*). Another test which is frequently imposed is flattening and doubling over. It is generally carried out both cold and at red heat. The tube is flattened and doubled over through 180° as shown in Fig. 103*d*.

For cold drawn weldless steel tubes the percentage increase in diameter allowed for the bulging test is usually not less than 15 per cent. for tubes less than 11 S.W.G. and not less than 12½ per cent. for tubes from 11 to 8 S.W.G.

For these tubes a crushing test is also specified. This consists in placing a piece of the tube 2 inches long on end and

hammering it down cold until it is reduced to 1⅛ inch long. It must stand this treatment without showing either a flaw or crack.

§ 79. **Drifting Test of Metals.**—Another workshop test for ductility, which is applied with ordinary shop appliances, is to bore holes of a given diameter near to the edge of the plate and open them by means of a conical drift (taper 1 in 10) until cracking occurs or a definite increase in diameter is reached. The hole is usually ⅝ inch diameter and 1½ inch from the edge of the plate.

Table XI gives comparative figures for various sizes of plate.

TABLE XI.

Material.	Thickness in Inches.	Original Size of Hole in Inches.	Enlarged Size of Hole, before Cracking, in Inches.
Wrought iron . . .	0·20	0·625	1·00
" " . . .	0·25	0·625	1·20
" " . . .	0·30	0·625	1·32
Mild steel . . .	0·30	0·625	1·50

§ 80. **Cupping Tests.**—Various methods have recently been employed for cupping sheet metal in order to obtain an indication of its ductility or drawing quality.

For gauges, of annealed material, below 0·060 inch in thickness the cupping ductility values give the same satisfaction as Brinell Hardness numbers do for gauges above that value.

(i) **The Erichsen Cupping Machine.**—This machine is now in extensive use in the United States of America. The sheet metal to be tested is placed between a die and an annular holder. A round-nosed tool of definite shape is forced against the specimen by means of a screw, the rotation of which is transformed into a horizontal forward motion of the tool. A cup is formed in the metal as indicated in Fig. 104, and the depth of this cup, registered in millimetres when fracture occurs, is a measure of the drawing quality of the material. The tool which is shaped with sides sloping down to an end radius, as illustrated, will test brass sheet up to a thickness of 0·10 inch.

Erichsen's standard curves showing the relationship between thickness of sheet and depth of impression for various metals are given in Fig. 105.

(ii) **Olsen Ductility Machine.**[6]—Some observers have experienced difficulty in recording the exact depth of cup at fracture.

With the Olsen machine the load required to produce the cupping is measured and the rupture of the cup can be readily noted from observation of the pressure which falls immediately failure occurs.

The apparatus can be obtained as a separate unit or for attachment to a universal testing machine.

In the former case the sheet metal 3 inches in diameter is placed over the die with the requisite amount of clearance for drawing and the hemispherical cupping tool is forced into it by means of worm gear, running in an oil bath and operated by a hand-wheel. The thrust is taken against a ball-thrust washer and the load is weighed by means of the pressure in a confined liquid. This pressure is read on a gauge.

The specimen can be observed directly and the depth of the cup at fracture is indicated on a dial.

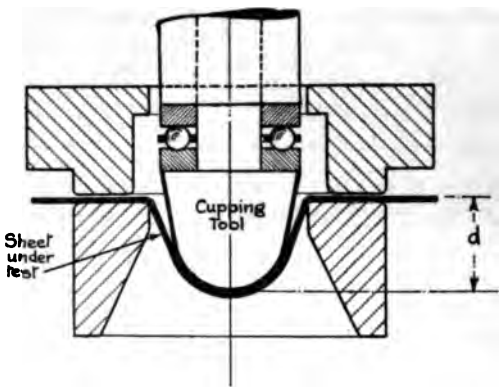


FIG. 104.—Erichsen cupping tool for testing metal sheets.

The tool moves vertically upwards in this machine while in the Erichsen apparatus it moves horizontally away from the operator.

With the universal testing machine attachment no provision is required for applying or measuring the load as these are carried out by the testing machine. The apparatus consists of the die and cupping tool, and arrangement is made for viewing the specimen, measuring the amount of the cup and furnishing the correct amount of clearance for drawing.

It is very important that the sheet to be tested should not be clamped tightly—a clearance of 0·002 inch should be allowed to permit the drawing of the metal to occur in a similar manner to that obtained in actual practice.

§ 81. **Falling Weight Tests** (called "drop test" in U.S.A.). —The falling weight test is considered to be a most useful test for rails and is given a prominent place in rail specifications. It is made by placing a piece of the rail, 4 to 6 feet long, on supports 3 feet apart, and dropping a heavy hammer, through varying distances, on to it at the mid-point of the span. The results

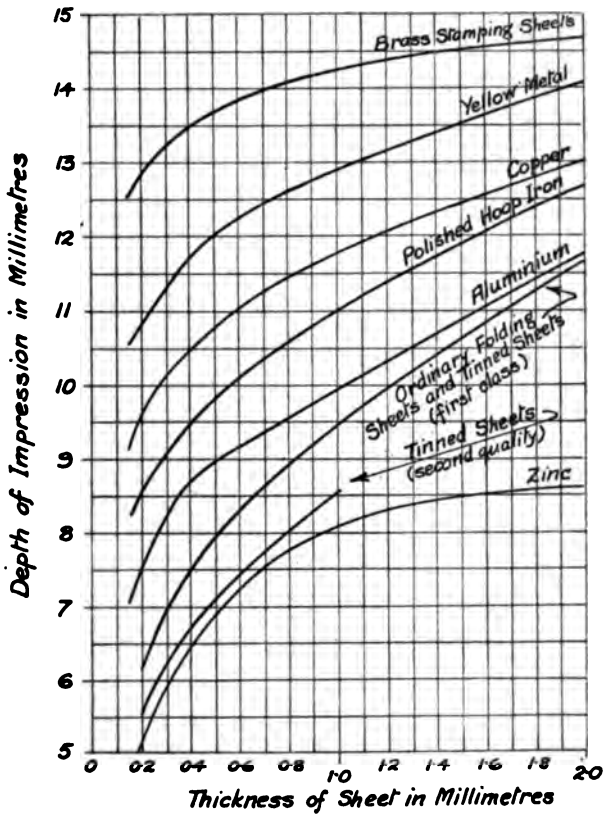


FIG. 105.—Erichsen's standard curves for trade qualities of metals.

show if the rail is brittle and the deflection gives a measure of the ductility.

P. H. Dudley[7] of U.S.A. says, "the physical properties of different sections can be compared and their chemical compositions adjusted from the results obtained on the standard drop testing machine".

The results are only comparative when carried out under the same conditions.

It is generally recognised that the weight of cup, distance apart of supports, height of fall, radius of striking faces and supports, and form of foundation must be specified. There is a difference of opinion, however, on these points, more especially in regard to the foundation of the machine.

Particulars of the standard machines usually adopted in the United States of America and in Great Britain are given in Table XII.

TABLE XII.

	U.S.A.	British.
FALLING WEIGHT .	of cast iron with steel striking die having a radius of striking face of 5 ins. and length of face of 12 ins. Total weight 2000 lbs.	of cast iron with steel striking face having a radius of 5 ins. Weight 2240 lbs.
ANVIL . . .	Solid iron casting 15 ins. thick and weighing 20,000 lbs.	Weight 26,880 lbs., area of base 45 sq. ft.
FOUNDATION . .	Anvil supported on 20 springs arranged in groups of 5 at each corner. The springs are supported by a cast-iron base plate which is bolted to a substructure with a timber floor in between. The floor to be 18 ins. longer than the base plate.	Anvil supported direct on 25 tons of concrete having an area of 100 sq. ft. No timber or springs between the test-piece and foundation.
SUPPORTS FOR TEST-PIECE (ANVIL DIES)	Pieces of steel having a cylindrical bearing surface of 5 in.	Steel bearers having a radius of 3 ins.
RELEASE . . .	A tripping device.	No automatic release allowed.

The atmospheric temperature is usually reported and due allowance is made for rails tested at or below 0° C.

The falling weight test is also applied to tyres and axles. For tyres a weight of 2240 lbs. is allowed to fall freely from 10, 15, 20 feet and upwards on the tread; the tyre being placed in its running position upon a heavy cast-iron anvil supported by a rigid concrete foundation. The tyre must deflect a given amount without fracture.

If d = internal diameter of tyre, as rolled, in inches
t = thickness of the centre of the tread, as rolled, in inches

minimum deflection $= \frac{d^2}{ct^2}$

where c = a constant depending on the breaking stress of the material.

TABLE XIII.

Value of "C".	Ultimate Stress in Tons per Square Inch.
45	42 to 49
50	50 ,, 55
55	56 ,, 62

For tramway tyres having a tensile ultimate strength of from 60 to 70 tons per square inch with an elongation of from 8 per cent. to 6 per cent., the deflection which the tyre has to stand without fracture is calculated from the formula:—

Deflection $= \frac{d^2}{75t^2}$ where

d = internal diameter of tyre, as rolled, in inches.
t = thickness of the centre of the tread, as rolled, in inches.

The weight is allowed to drop from a height of 3 feet, increasing by 1 foot for consecutive blows, until the required deflection is obtained.

§ 82. **Falling Weight Test on Axles.**—Axles are placed on supports whose distance apart varies from 3 feet for axles under 4 inches at the centre to 5 feet for axles over 6 inches diameter.

The axle is turned after the first and third blows from a 2240 pound hammer, falling 16 feet for diameters under 4 inches to 35 feet for those over 6 inches diameter, and must stand five blows without fracture. The exact span and height of fall is specified for various diameters of axle between the limits given above, and can be obtained from the British Engineering Standards Association Specification for Axles (No. 24, Part I. See Appendix).

§ 83. **Drop Test of Tyres.**—Tyres are also subjected to a drop test. The tyre is allowed to drop freely, in a running position from a specified height, upon a rail fastened to an iron block

of not less than 2 tons weight. The tyre is then turned through 90° and dropped a second time. The height of fall depends upon the diameter of the tyre (see Table XIV).

TABLE XIV.

Height of Fall in Feet.	Internal Diameter of Tyre in Feet.
5	Up to $3\frac{1}{2}$
4	$3\frac{1}{2}$,, $5\frac{1}{2}$
$3\frac{1}{2}$	$4\frac{1}{2}$,, $5\frac{1}{2}$
3	$5\frac{1}{2}$,, $6\frac{1}{2}$
$2\frac{1}{2}$	Over $6\frac{1}{2}$

REFERENCES FOR CHAPTER VII.

[1] Johnson, "Materials of Construction," 1918 edition, p. 10.
[2] Unwin, "Testing Materials of Construction," 1910 edition, p. 266.
[3] Roberts, "Engineering Research," "Inst. Mech. Eng. Proc.," July, 1913.
[4] Capp, "Proc. Amer. Soc. Test. Mat.," 1907, Vol. VII, p. 624.
[5] Firth, "Inst. Civ. Eng. Proc.," Vol. CLV, p. 254.
[6] Olsen, T. Y., "Ductility Testing Machines," "Proc. Amer. Soc. Test. Mat.," 1920, Vol. XX, Part 2, p. 398.
[7] Dudley, "Proc. Amer. Soc. Test. Mat.," 1910, Vol. X, p. 232.

CHAPTER VIII.

MECHANICAL TESTING OF HARD DRAWN WIRE.

§ 84. THE British Standard Specification for hard drawn copper wire is based on the methods and results which have been successfully used by the Post Office for many years.

The mechanical tests required are:—

(i) Tensile test (for breaking strength).
(ii) Twisting test } (for ductility).
(iii) Wrapping test }

The American Society for Testing Materials deprecate the use of twisting and wrapping tests and are of opinion that, with suitable apparatus, a combination of tests for the tensile strength and elongation ensure a satisfactory standard of quality. On the Continent the practice is to use a bend test in which the wire is bent backwards and forwards through 180° until fracture occurs.

It is essential that, for a specification which is to be used for the acceptance or rejection of supplies, the tests should be capable of being easily applied in practice. It is doubtful whether, with the apparatus which is at present available in most works, the small extensions which are obtained on hard drawn copper wire of the smallest sizes can be measured with the requisite accuracy.

§ 85. **Tensile Tests.**—These are best carried out in a testing machine of the lever type which can be easily adjusted and the accuracy checked.

For tensile strength the pieces of wire, as cut from the coil, are placed in the grips of the testing machine without any previous straightening. Nine-tenths of the minimum specified breaking load is applied to the test-piece as rapidly as possible and the remaining tenth at a uniform rate until the specimen breaks. The time from start to finish of the test occupies about ten seconds—the last tenth taking about half of this time.

It is found that the rate at which the load is applied has a

marked effect upon the results obtained. Table XV gives the results of some experiments on hard drawn copper and aluminium in which the time of loading is varied. In one case the procedure recommended above has been adopted while in the other the total time taken is approximately twelve times as long. It is seen that the quicker loading gives results which are 1 per cent. to 8 per cent. high. The authors have had instances of hard drawn copper wires which have sustained loads for two hours before ultimately breaking. It is evident that the figures obtained from quick testing on hard drawn copper and aluminium only give comparative resistances of the materials to tensile loads and do not represent actual properties of those materials.

TABLE XV.

TEST ON HARD DRAWN COPPER AND ALUMINIUM AT DIFFERENT RATES OF LOADING.

Diameter of Wire in Inches.		0·104.	0·137.	0·166.	0·187.	0·212.
Copper	Ultimate stress in tons per sq. in. slow	28·3	27·8	26·6	26·6	25·5
	Ultimate stress in tons per sq. in. fast	29·7	28·5	27·4	27·2	26·0
	Increase in strength per cent.	5·0	2·5	3·0	2·3	2·0
Aluminium	Ultimate stress in tons per sq. in. slow	—	10·3	10·1	9·1	9·1
	Ultimate stress in tons per sq. in. fast	—	10·9	10·2	9·8	9·4
	Increase in strength per cent.	—	5·8	1·0	7·8	3·3

Cold drawing of copper and aluminium increases its tensile strength. Some results obtained by T. Bolton [1] on a sample of copper drawn without annealing are given in Table XVI. These show an increase in ultimate tensile stress from 29·0 tons per square inch to 41·6 tons per square inch by drawing from 0·194 inch diameter to 0·015 inch diameter.

Specification figures for hard drawn aluminium suggested by Welbourn [2] are given in Table XVII. The percentage increase of strength due to drawing is seen to be of about the same amount as for copper.

TABLE XVI.

RESULTS OBTAINED BY T. BOLTON ON COPPER DRAWN WITHOUT ANNEALING.

Diameter. Ins.	Ultimate Tensile Strength. Tons per Sq. In.	Elongation on 10 Ins. Per Cent.
0·194	29·00	2·1
0·128	30·39	1·2
0·079	31·36	1·0
0·072	33·32	1·0
0·064	33·28	1·1
0·048	33·84	1·0
0·028	33·92	1·5
0·018	38·58	2·0
0·015	41·60	2·1

TABLE XVII.

SUGGESTED TEST RESULTS FOR HARD DRAWN ALUMINIUM CONDUCTORS (BY WELBOURN).

S.W.G.	Diameter. Ins.	Ultimate Tensile Strength. Tons per Sq. In.	Extension on 5 Ins. Per Cent.	Wrapping Test.
4	0·232	11·0	3·0	Three times round its own diameter and three times off.
6	0·192	12·0	3·0	
8	0·160	13·0	3·0	
10	0·128	13·5	3·0	
12	0·104	14·0	2·5	
14	0·080	14·5	2·5	
16	0·064	14·75	2·5	

Various formulæ have been suggested to connect ultimate stress with the diameter of the wire. Pye [3] has suggested, for hard drawn copper wire not exceeding 0·5 inch diameter, the formula

$$T = 30 - 20D$$

where T = ultimate stress in tons per square inch
D = diameter of the wire in inches.

Figures calculated from this formula are rather lower than are usually obtained in practice and a modification, viz.—

$$T = 31 - 20D,$$

has been proposed.

Figures calculated from the following formulæ (suggested by Dr. Unwin) agree very well with actual results :—

$P = 2600D + 30800D^2$ for wires over 0·16 inch diameter
$P = 500D + 44000D^2$ for wires of 0·157 inch diameter and less

where P = breaking load in lbs. and D = diameter of the wire in inches.

For hard drawn aluminium wire B. Welbourn suggests the formula :—

$$T = 16{\cdot}5 - 24D$$

where T = ultimate stress in tons per square inch
D = diameter of the wire in inches.

It is very difficult, however, to obtain a formula to represent results which can be expected from a whole range of sizes of wire, and a much more satisfactory specification is produced by compiling a table to give actual figures for all gauges.

Effect of Temperature on the Tensile Strength.—Some tests carried out by the authors [4] on 50-feet lengths of hard drawn copper wire with a slow rate of loading show that the reduction in breaking load, due to temperature variation from − 12° C. to + 60° C., appears to be approximately 0·1 per cent. of the breaking load at 15° C. per degree centigrade rise of temperature. For hard drawn bronze wire the effect is rather less than this value. Similar results have been obtained by experiments carried out in India and also by B. Welbourn.

Effect of Kinks on Breaking Strength.—There is a reduction in the breaking strength due to kinks in the wire caused by faulty winding of the coil or other causes ; this reduction may be as much as 5 per cent. of the breaking load, for hard drawn copper, with the type of kink which is frequently met with in practice.

§ 86. **Extension.**—Where extension of copper wire is specified a 10-inch gauge length is usually adopted. It should be noted that by fixing the gauge length for all sizes of wire, the results do not follow Barba's Law of similarity (see § 55). On a fixed gauge length the smaller sizes of wire give less percentage extension than the larger ones if the material has the same mechanical properties in each case.

The elongation of hard drawn copper wire on a 10-inch gauge length, varies from 3½ per cent. to 1 per cent. according to the gauge of the wire. For soft copper in all gauges the per cent. extension on 10 inches is 30 per cent. to 40 per cent.

For hard drawn copper wire Pye [3] suggests the formula :—

$$e = 5D$$

where e = the percentage extension on 10 inches
and D = the diameter of the wire in inches.

The values given by this formula are lower than those usually obtained.

For hard drawn aluminium wire no fixed gauge length is universally adopted. Welbourn suggests 5 inches but 10 inches and 2 inches are sometimes used.

§ 87. **Modulus of Elasticity in Tension.**—The modulus of elasticity of wires can be obtained on short lengths by means of a mirror extensometer (§ 115). For these tests the wire is usually straightened by hand and inserted in the grips of the testing machine, giving a length of 10 inches. Readings taken during the first loading of the wires always give low values of the modulus, due to the pulling out of the very small bends left by the hand straightening. If the limit of proportionality is slightly exceeded and the load released subsequent tests within this value of the load give higher values, which are constant. Average results from a large number of tests on hard drawn copper, aluminium and steel wire are given in Table XVIII. The difference in the values obtained from the initial and subsequent loadings is from 2 per cent. to 3 per cent.

TABLE XVIII.

MODULUS OF DIRECT ELASTICITY (E) ON SHORT LENGTHS OF WIRE.

	Modulus of Elasticity in Lbs. per Square Inch.		
	Hard drawn Copper.	Hard drawn Aluminium.	Steel.
First loading . .	$17{\cdot}8 \times 10^6$	$9{\cdot}7 \times 10^6$	$27{\cdot}8 \times 10^6$
Second and subsequent loadings . . .	$18{\cdot}3 \times 10^6$	$9{\cdot}9 \times 10^6$	$28{\cdot}4 \times 10^6$

Results of a series of determination of "E" for hard drawn copper wire are given in Report No. 55 of the British Engineering Standards Association. In these tests the "apparent" modulus was obtained on 50-feet lengths of wire. They were made without previous straightening and also after the limit of proportionality had been exceeded. The results (Table XIX) on the unstrained wires are from 14½ per cent. to 32 per cent. low. The greatest variation in the results being with the wire of 0·158 inch diameter which was initially slightly kinked throughout its length.

The value of "E" for hard drawn copper has been determined by Woodhouse and B. Welbourn on long lengths of wire and stranded conductors by suspending the wire from columns and measuring the dip at the centre. Both experimenters calculate the modulus by assuming that the dip is very small

compared to the span and that the form of the curve taken by the suspended wire is parabolic. The stress in the wire is taken as equal to that at the mid-point of the span.

TABLE XIX.

MODULUS OF ELASTICITY OF HARD DRAWN COPPER WIRE IN LONG LENGTHS.

	Value of "E" in Lbs. per Sq. In.		
	Test No. 1. Diam 0·158.*	Test No. 2. Diam. 0·138.	Test No 3. Diam. 0·138.
First loading . .	12·3 × 10^6	15·0 × 10^6	15·3 × 10^6
Subsequent loadings .	18·0 × 10^6	18·2 × 10^6	17·9 × 10^6

* This wire has slight kinks throughout its length.

(i) Woodhouse,[5] who holds the opinion that tests for modulus on 10-inch lengths are of doubtful value, uses three supports forming two equal spans for his tests. Two wires are suspended over the two spans and their ends clamped together. One wire is then carefully removed from the central support and suspended on the double span. The dips at the centre (d and d_1, Fig. 106)

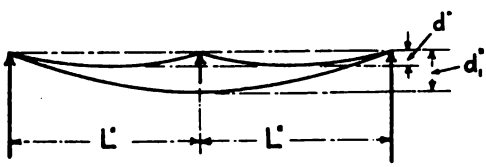


FIG. 106.—Modulus of elasticity of long spans of wire (Woodhouse's method).

under the two conditions are then measured and the modulus obtained from the elastic extension and the difference of the stresses in the two wires calculated from the following formulæ:—

If (Fig. 106) W = weight of the wire per inch run, in lbs.
L = length of each span in inches
A = cross-sectional area of the cable in square inches
d = dip for a single span (L) in inches
d_1 = dip for a double span (2L) in inches
E = modulus of elasticity in lbs. per square inch
s = length of the wire on span L in inches.

Difference of stress in the two wires $= \frac{WL}{8A}\left(\frac{4}{d_1} - \frac{1}{d}\right)$.

Elastic elongation on length "s" $= \frac{2}{3L}(d_1^2 - 4d^2)$

where $s = \frac{8d^2}{3L}$.

(ii) Welbourn[6] suspends the wire from two supports and pulls the dip to about 6 inches, he then lets out to about 12 inches dip, and accurately measures the dip (d).

An extra length of wire is then bound to the first wire and the new dip "d_1" measured. On the removal of the extra load the dip "d" is again obtained if the limit of proportionality has not been exceeded.

If W = weight in lbs. per inch run of the unloaded strand
W_1 = weight in lbs. per inch run of the loaded strand
d = dip in inches for load W
d_1 = dip in inches for load W_1. This load includes the weight of clips, etc., for binding the wires together
A = cross-sectional area in square inches
L = length of span in inches
E = modulus of elasticity in lbs. per square inch

then $E = \frac{3L^4(W_1/d_1 - W/d)}{64A(d_1^2 - d^2)}$.

It is essential for these tests that there is still air and that the temperature remains constant during the test. Welbourn from his experiments suggests as working figures for hard drawn wire and strand the values given in Table XX.

TABLE XX.

Modulus of Elasticity (E) for Hard Drawn Copper Wire and Strand under Working Conditions.

7 strand	$20{\cdot}0 \times 10^6$	lbs. per sq. in.
19 ,,	$17{\cdot}5 \times 10^6$	,, ,,
37 ,,	$15{\cdot}5 \times 10^6$	,, ,,
61 ,,	$14{\cdot}0 \times 10^6$	,, ,,
91 ,,	$12{\cdot}5 \times 10^6$	,, ,,
Wire	$20{\cdot}0 \times 10^6$	,, ,,

§ 88. **Twisting Test.**—For this test the wire is gripped in two vices and twisted by one of the vices being made to revolve at a speed not exceeding one revolution per second. The twists are reckoned by means of an ink mark which forms a spiral on the wire during torsion and the full number of twists must be visible between the vices.

A lathe can be adapted to carry out the tests but it is usual to have a special machine for the purpose such as is shown in Fig. 107 and made by W. & T. Avery, Ltd. The test-piece (T) is clamped in the grips (A and B) and the sliding counter (P) set at zero. The wire is twisted by the handle and gearing (G) and the pointer of the counter gives the number of twists as a check on the figure counted from the ink spiral. A suitable ink mark is made by a mixture of lamp black and shellac varnish.

The number of twists increases—

(*a*) As the length between the vices is increased.

(*b*) As the diameter of the wire becomes smaller.

The number of twists which a wire will stand is larger if the speed of twisting is increased.

It is usual to tabulate the number of twists required for each size of wire and specify the distance between the vices. For 300 lbs. (0·137 inch diameter) hard drawn copper wire and larger sizes the vice distance is usually 6 inches, for wire smaller than this 3 inches is used.

For steel wire the vice distance is generally 6 inches, except for wires of 150 lbs. per mile (0·104 inch diameter) or less, in which case the vices are placed 3 inches apart. Some specifications require the vice distance to be 100 times the diameter of the wire.

§ 89. **Wrapping Test.**—For this test the wire is wrapped in six turns round its own diameter, unwrapped, and again wrapped in six turns round its own diameter in the same direction as the first wrapping. Hard drawn copper wire must stand this treatment without breaking. This test can conveniently be carried out by hand in an ordinary bench vice. The wire held horizontally is bent round the top of the vice and wrapped round its own diameter as indicated in Fig. 108. It is usual to make either eight or nine turns on the first wrapping so that when the wire is unwrapped six turns, at least two turns are left.

On the Continent the wrapping test is sometimes less severe, the wire being wrapped round a cylinder which is fifteen times its own diameter.

§ 90. **Bending Test.**—In this country this test is principally used on steel wire. The wire is held in a vice and bent backwards and forwards through 180° (i.e. through 90° on either side of the vertical), the grips having radii of a fixed amount—5 mm. for wires smaller than eight gauge (0·160 inch diameter) and 10 mm. for wires larger than eight gauge.

Special machines can be purchased for carrying out the test,

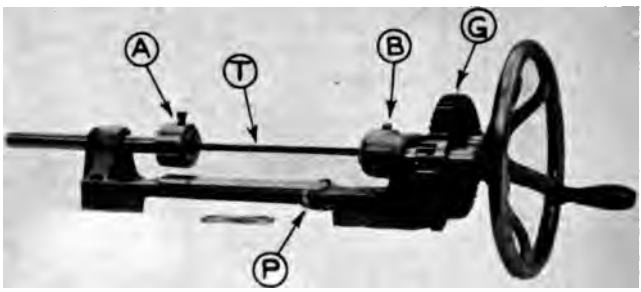


FIG. 107.—Twisting machine for wire.

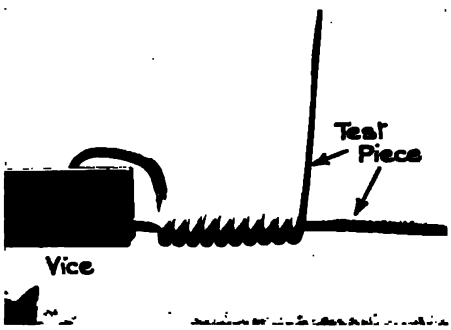


FIG. 108.—Wrapping test.

[*See p.* 138.

FIG. 109.—Commercial deflectometer.

[*See p.* 142.
[To face p. 138.

most of these grip the wire at the point where it is bent. If there is any slipping at the grips the number of bends to fracture is too large, whereas if the wire is soft, and it is damaged by tight clamping, the results are on the low side. This source of error can be avoided if the machine is so designed that the radius round which the wire is bent is away from the gripping device but is firmly held while the bending is in progress.

REFERENCES FOR CHAPTER VIII.

[1] Bolton, "Inst. of Metals Journal," 1911, Vol. II, p. 188.
[2] Welbourn, "Inst. Elect. Eng. Journal," Vol. LII.
[3] Pye, "Mechanical Properties of Hard Drawn Copper," "Inst. of Metals Journal," 1911, Vol. II. p. 165.
[4] "British Engineering Standards Association," Report No. 55.
[5] Woodhouse, "Inst. Elect. Eng. Journal," Vol. LXIV.
[6] Welbourn, "Inst. Elect. Eng. Journal," Vol. LIV, p. 54.

CHAPTER IX.

TESTING CAST IRON.

§ 91. **Transverse Test.**—Owing to the ease with which it can be carried out, the transverse test or cross-breaking test has been universally adopted as the standard for cast iron. The test is carried out by breaking the test-bar as a beam loaded centrally. The strength is measured by the centre load which the bar will carry. The deflection is also usually specified because, when taken in conjunction with the load, it gives an approximate measure of the toughness of the cast iron. A suitable machine for carrying out the test is described in § 43. It is essential that the form of the test-bar should be standardised in order to obtain comparative results, but unfortunately the standards which are in use in various countries are different. Particulars are given in Table XXI.

TABLE XXI.

PARTICULARS OF STANDARD TEST BARS FOR CAST IRON.

	English Standard.	American Standard.	German Standard.
Cross section of bar in inches	1 in. wide 2 ins. deep	1½ in. diameter	1 1/16 in. diameter
Length of bar in inches	40	15	25⅛
Span in inches	36	12	23·62
How cast	on edge	vertically	horizontally

The general experience, in casting bars of the various standards in use, is that there is a little more difficulty in obtaining sound bars cast to the English section than in the case of either the American or German bars.

Machined bars are generally weaker than unmachined specimens.[1]

If W is the central load, L the span, Z the modulus of the section, and f the stress in the bar.

Then within the elastic limit

$$\frac{WL}{4} = fZ \text{ or } f = \frac{WL}{4} \cdot \frac{1}{Z}.$$

Above the elastic limit the stress calculated from the formula varies, for the same material, with the form of the section, but if the breaking load (W_b) is substituted for "W" a value of "f" is obtained which is a measure of the quality of the material for bars of similar section and is called the modulus of rupture.

G. Hailston,[2] in 1914, as a result of a series of experiments on cast iron when tested by cross breaking, finds that, whereas the ratio of the breaking loads for 1 × 2 × 36 inches (span) and 1 × 1 × 12 inches (span) beams is 1·333 if the formula W × L/4 = fZ is taken as applying up to the point of rupture, the actual value is 1·153 if the pieces are machined and 1·146 when tested with the skin left on. He further finds that the best test-bar to give the most consistent and comparable results both with breaking load and deflection is $2\frac{1}{8}$ × $1\frac{5}{8}$ × 42 inches, cast on the flat and machined down to 2 × 1 inches and tested on a span of 36 inches. The rate of testing should not exceed 112 lbs. in less than fifteen seconds.

The results in Table XXII of tests on grey cast iron by Mathews,[3] shows that the modulus of rupture decreases as the span increases; the cross section being circular ($1\frac{1}{4}$ inch diam.) and kept constant.

TABLE XXII.

A Comparison of the Results on Grey Cast Iron, showing Decrease of the Modulus of Rupture as the Span Increases.

Silicon. Per Cent.	Span. Inches.	Mean Centre Load. Lbs.	Modulus of Rupture. Lbs. per Sq. In. S_m.	Tensile Strength. Lbs. per Sq. In. S_t.	$\frac{S_m}{S_t}$.
1·5	12	3000	47,100	25,600	1·84
	18	1935	45,600		1·78
	24	1425	44,700		1·75
2·0	12	2900	45,500	24,370	1·87
	18	1835	43,200		1·78
	24	1265	39,700		1·63
2·5	12	2880	45,200	24,660	1·83
	18	1905	44,900		1·82
	24	1400	44,000		1·78

TABLE XXIII.

EXPERIMENTS ON TRANSVERSE STRENGTH. COMPARISON ON ENGLISH, GERMAN AND AMERICAN STANDARD BARS.

Description.	Dimensions. Inches.	Span. Inches.	Mean Centre Load. Lbs.	Deflection. Inches.	Modulus of Rupture.	
					Lbs./Sq. In.	Tons/Sq. In.
English standard, cast on flat	1·07 × 1·98	36	2840	0·38	36,500	16·3
German standard, cast horizontal	1·14 in. diam.	23·62	1210	0·32	49,200	22·0
American standard, cast vertical	1·24 in. diam.	12	3230	0·11	51,800	23·1
English standard, cast on edge	1·02 × 2·04	36	3370	0·40	42,900	19·2
German standard, cast horizontal	1·23 in. diam.	23·62	1660	0·36	53,700	24·0
American standard, cast vertical	1·25 in. diam.	12	3380	0·135	52,300	23·3

Table XXIII compiled from figures given by J. E. Stead[4] give a comparison of results obtained on British, American and German standard bars. His conclusion is that it is desirable that any bar for testing for deflection by transverse stress should not be less than 24 inches long, as with shorter bars than this it is very difficult to measure to the required degree of accuracy except with very delicate measuring instruments.

In commercial work a deflectometer of the type shown in Fig. 109 is generally used. It consists of a base (B) the bottom of which is carefully planed. This base carries a scale (S) along which a lever moves. The adjusting screw (A) of the lever is arranged under the transverse tool so as not to be affected by the breaking of the specimen.

A simple arrangement which is sometimes adopted is to use a Brown and Sharp lathe indicator under the transverse tool at the centre of the beam.

The following observations have been recorded as the result of careful experiment:—

(1) Square bars, in general, exhibit a slightly higher modulus of rupture than round bars of equal area. Tests by a committee of the American Society of Mechanical Engineers[5] give an average of about 5 per cent. higher.

(2) Bars cast horizontally are strongest when the load is applied against the cope face.

(3) Rough bars are stronger than planed bars.[6]

(4) Tumbling in a rattler increases the hardness of the skin and therefore improves the strength.

(5) Bars run with hot metal are weaker and deflect more than bars run with dull metal.[7]

(6) Tapping a bar with a hammer during test reduces its strength.[7]

(7) For bars of the same proportions, the modulus of rupture is lower as the section is larger.[8]

(8) A wide bar gives a higher and a deep bar a lower modulus of rupture.[8]

With the English standard test-pieces (1 inch wide, 2 inches deep, 42 inches long, and 36 inches span) the strength of cast iron is usually specified by its breaking load in cwts., figures of 18, 28 and 38 (cwts.) corresponding to poor, fair, and good cast iron. A usual specification is that the cast iron shall sustain a load of 30 cwts. at the centre with a deflection of not less than $\frac{5}{8}$ inch.

§ 92. A form of report which is suitable for transverse tests is given in Table XXIV (page 144). It enables the salient points of the results to be seen at a glance and meets all ordinary cases on the testing of cast iron.

§ 93. **Effect of Temperature on the Transverse Strength of Cast Iron.**—Cast iron loses very little of its strength and toughness up to a temperature of 400° C. The following sets of experimental results (Table XXV) by Meyer[9] show this very clearly.

TABLE XXV.

EFFECT OF TEMPERATURE ON THE TRANSVERSE STRENGTH OF CAST IRON.

Temperature. °C.	Modulus of Rupture. Tons per Sq. In.	Maximum Deflection. Inches.
18	23·5	0·31
66	22·2	0·30
268	21·1	0·28
297	19·9	0·30
620	12·1	0·55
807	7·6	0·94
18	23·6	0·30
85	21·9	0·28
155	21·3	0·28
370	21·0	0·30
580	16·0	0·57
810	6·2	0·79

TABLE XXIV.

TRANSVERSE TESTS OF MATERIALS CARRIED OUT ON CAST IRON TEST-PIECES SUPPLIED BY MESSRS. H. C. L. & CO., LTD., FOR WHOM THE TESTS WERE MADE.

Test Number.	Identification Marks.	Distance between Supports, Inches.	Dimensions.		Deflection at Centre in Inches.								Breaking Load at Centre in Lbs.	Deflection at Fracture in Inches.	Remarks.
			Breadth, Inches.	Depth, Inches.	5 Cwts.	10 Cwts.	15 Cwts.	20 Cwts.	25 Cwts.	30 Cwts.	35 Cwts.	40 Cwts.			
ATM1	HCL1	36	1·04	2·04	·046	·095	·146	·198	·261	·330	·405	—	4266	0·46	
ATM2	HCL2	36	1·02	2·02	·047	·096	·146	·198	·255	·325	·404	—	4315	0·46	

Order No. 262H
Reference, Eng/ATM.
Tested by R. G. B.

Director.
Date, 28th July, 1921.

§ 94. **Tensile Strength of Cast Iron.**—It is important when making tensile tests on cast iron to ensure that the pull is axial as this material is greatly weakened by oblique or eccentric loading. For accurate testing, shackles with spherical seats should be employed (see § 45 (iii)), the test-bar should be cast in one with the work and turned to a suitable size; care being taken to avoid rapid changes of section near the part of the specimen under test.

The size of the bar from which the test-piece is taken affects the results obtained, bars of larger section giving, as a rule, lower results.

Tables XXVI and XXVII give results recorded by J. E. Stead[4] on test-pieces prepared from bars of various sizes which have been cast in different ways.

Table XXII, § 91 (page 141), gives results obtained by Mathews[3] on cast iron containing various percentages of silicon.

TABLE XXVI.

TENSILE TESTS ON CAST IRON.

Test-pieces 0·798 in. diameter, 0·500 sq. in. area.

Description.	No. of Tests.	Ultimate Stress. Tons per Sq. In.	Average Per Cent. Variation from Average.	Remarks.
Cast on flat in bars 2 in. × 1 in.	4	11·2	1·3	All test-pieces turned.
Cast horizontally, 1·187 in. diameter	4	12·2	1·8	
Cast vertically, 1¼ in. diameter	4	12·2	1·8	

TABLE XXVII.

TENSILE TESTS ON CAST IRON.

Test-pieces 0·798 in. diameter, 0·500 sq. in. area.

Description.	No. of Tests.	Ultimate Stress. Tons per Sq. In.	Average Per Cent. Variation from Average.	Remarks.
Cast horizontally as a test-bar, 1¼ in. diam.	4	13·9	0·9	Tested with skin on.
Cast horizontally, 1·187 in. diameter	6	13·4	3·2	Turned to 0·798 in. diameter.
Cast vertically, 1·187 in. diameter	6	13·5	1·8	Turned to 0·798 in. diameter.

Only test-pieces which broke with a sound fracture are included in Tables XXVI and XXVII.

TABLE XXVIII.

COMPARISON OF MODULUS OF RUPTURE AND TENSILE STRENGTH OF CAST IRON.

Type of Test-bar and Authority.	Modulus of Rupture. Tons per Sq. In. (A).	Ultimate Tensile Stress. Tons per Sq. In. (B).	Ratio, A/B.
American Standard (Mathews)	21·0	11·4	1·84
	20·3	10·9	1·86
	20·2	11·0	1·84
American Standard (Stead)	23·1	12·2	1·89
	23·3	13·5	1·72
English Standard (Stead)	16·3	11·2	1·46
	19·2	13·9	1·38
German Standard (Stead)	22·0	12·2	1·80
	24·0	13·4	1·79

A comparison between the modulus of rupture and the tensile strength is given in Table XXVIII.

An attachment is added to the latest design of transverse testing machine made by W. & T. Avery, Ltd., for carrying out tensile tests on cast iron (see § 43).

§ 95. **Effect of Temperature on the Ultimate Tensile Strength of Cast Iron.**—Tensile tests on cast iron at varying temperatures agree with the conclusions from the transverse tests (see § 93), viz. that there is only very small effect up to a temperature of 400° C.

Average results from three series of experiments are given in Table XXIX.

TABLE XXIX.

EFFECT OF TEMPERATURE ON THE TENSILE STRENGTH OF CAST IRON.

Temperature. °C.	Tensile Ultimate Strength in Tons per Sq. In.		
	Sample A.	Sample B.	Sample C.
15	16·2	13·0	13·0
200	15·7	12·8	12·1
300	16·1	11·8	12·1
400	16·8	12·8	12·6
500	13·1	11·8	11·2
600	9·2	7·8	7·6
700	4·6	4·8	4·6

§ 96. **Crushing Strength of Cast Iron.**—The crushing strength of cast iron is obtained on cylinders or prisms in which

the ratio of the height to the least lateral dimension is between one and three.

The crushing strength is usually about five times the ultimate tensile stress and samples of bad, good and very good cast iron should give a crushing stress of 30, 40, and 50 tons per square inch respectively.

With the same metal specimens from small castings are stronger than those from large ones.

Fig. 26, § 28, shows the form of the fracture of cast iron.

§ 97. **Resistance of Cast Iron to Direct Shear and Torsional Shear.**—As the result of experiments in direct shear by Platt and Hayward,[10] it was thought that the shearing strength of cast iron was about 5 to 6 tons per square inch. Izod,[11] however, by using more perfect apparatus, has obtained much higher figures, and these are confirmed by Goodman. The results of these tests together with the figures obtained from gunmetal and mild steel, for comparison, are given in Table XXX.

TABLE XXX.

SHEARING TESTS ON CAST IRON.

Material.	Ultimate Tensile Stress, F_t, Tons per Sq. In.	Ultimate Shear Stress, F_s, Tons per Sq. In.	Ratio, $\frac{F_s}{F_t}$	Calculated Coefficient of Torsional Strength. Tons per Sq. In.	Authority.
Cast iron A	9·7	14·8	1·52	—	Izod
,, ,, B	13·4	17·4	1·11	—	,,
,, ,, C	11·3	13·9	1·22	—	,,
,, ,, D_1	13·7	16·1	1·18	—	,,
,, ,, D_2	13·5	14·8	1·10	—	,,
Cast Iron	10·9	12·9	1·18	—	Goodman
,, ,,	11·5	13·0	1·13	16·0	,,
Gunmetal	12·1	12·5	1·03	—	Izod
,,	12·4	17·4	1·40	—	Goodman
,,	13·8	16·0	1·16	21·0	,,
Mild steel	26·9	21·0	0·78	—	Izod
,, ,,	23·6	18·9	0·81	—	Goodman

The point of interest in Table XXX is the fact that the shearing strength of cast iron is higher than the ultimate tensile strength. Goodman says that with the exception of specimens which are defective on account of blow holes or sponginess he has never had a single instance of a specimen of cast iron giving a lower result in shear than in tension.

Frémont is of opinion that the shear test gives a very useful indication of the quality of cast iron if the sample tested truly represents the material of the casting. He has devised a special test for this purpose.[12] A small piece of the actual casting, 25 mm. diameter and 20 mm. long, is detached by a trepanning tool. The specimen is placed within a block holding a fixed blade and is cut by a movable blade which is forced into the specimen by a weight acting on a lever. The force of rupture is estimated from the weight and leverage. Since the diameter of the hole bored in the casting is only about $1\frac{1}{4}$ inch the casting is not spoiled by this method of procedure.

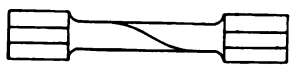


FIG. 110.—Typical torsion failure in cast iron.

Under torsional shear, a round bar of cast iron invariably fractures along a helix whose angle is 45°, that is to say it occurs where the tensile stress is a maximum and indicates that cast iron has a lower resistance to tension than to shearing. This conclusion confirms the direct shear results of Izod and Goodman. A typical torsion fracture is shown in Fig. 110.

REFERENCES FOR CHAPTER IX.

[1] Segundo and Robinson, "Inst. Civ. Eng. Proc.," Vol. LXXXVI, p. 248.
[2] Hailston, "Iron and Steel Inst. Journ.," 1914.
[3] Mathews, "Proc. Amer. Soc. Test. Mat.," Vol. X, p. 299.
[4] Stead, "Proc. Int. Assoc. Test. Mat.," 1912, Vol. VI, p. 4.
[5] "Trans. Amer. Soc. Mech. Eng.," Vol. XVI, pp. 543 and 1066; Vol. XVII, p. 675.
[6] Segundo and Robinson, see No. 1.
[7] Unwin, "Testing of Materials of Construction," 1910 edition, p. 291.
[8] Millar, "Inst. Civ. Eng. Proc.," Vol. LVIII, p. 222.
[9] Meyer, "Stahl und Eisen," Vol. XXVI, pp. 1270-71.
[10] Platt and Hayward, "Inst. Civ. Eng. Proc.," Vol. XC, p. 382.
[11] Izod, "Inst. Mech. Eng. Proc.," Jan., 1906.
[12] Frémont, "Comptes Rendus," Dec. 9th, 1918.

CHAPTER X.

INFLUENCE OF SHAPE AND TIME ON THE PROPERTIES OF MATERIALS.

§ 98. AN abrupt change in the cross section of a tensile or transverse test-bar causes :—

(*a*) A diminution of the elongation at the reduced section due to the shoulders of the notch or groove.

(*b*) The stress to be highly concentrated at the periphery of the groove or notch.

There are thus two effects, the suppression of the drawing out of the material causes a gain of strength while the inequality of the stress on the section of fracture gives a reduction in strength.

With a brittle material, e.g. cast iron, the elongation is negligible and in consequence the effect of a groove is to cause a reduction of strength. On the contrary a grooved mild steel test-piece is stronger than a plain bar of the same material because the suppression of the drawing out causes an increase in strength which is greater than the effect due to concentration of stress at the groove acting in the opposite direction.

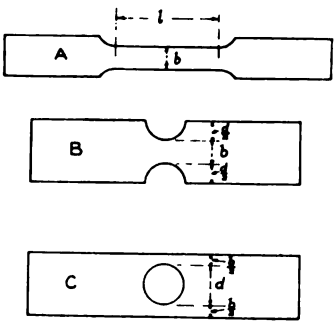


FIG. 111.—Test-pieces for strength tests of perforated bars.

§ 99. **The Effect of Perforating on the Strength of Mild Steel Plates.**—In the discussion on a paper by W. Hackney before the Inst. of Civ. Eng., Stromeyer [1] describes experiments carried out to determine the effect of perforation on the tensile strength and elongation of boiler plates. The forms of test-bars that he used are given in Fig. 111 and the results are given in Table XXXI.

TABLE XXXI.

STRENGTH OF PERFORATED PLATES.

Form.	Dimensions.		Ratio, $\frac{b}{d}$	Elongation, Per Cent.			Ultimate Stress. Kilos per Sq. Mm.	
	Width, b Mm.	Thickness, t Mm.		Of Hole.	In 50 Mm.	In 200 Mm.		
A	35	12	—	—	—	25½	44·0	
B	46·8	12	1·94	50	26	—	47·4	
	31·8	12	1·32	40	18	—	48·0	Mean 47·8
	18·0	12	0·75	27½	14	—	47·7	
	12·5	12	0·52	21	12	—	48·0	
C	54·0	12	2·25	54	28	—	46·6	
	44·0	12	1·83	50	26	—	47·0	
	34·0	12	1·42	46	22	—	45·8	
	28·4	12	1·18	41½	22	—	45·0	Mean 45·7
	23·3	12	0·97	37½	20	—	48·8	
	18·6	12	0·77	33½	16	—	45·2	
	13·0	12	0·54	25	14	—	45·5	
	7·6	12	0·32	21	10	—	45·1	

The test-pieces are all cut from one piece of plate 12 mm. (t) thick and the holes are all 24 mm. (d) diameter. The width (b) varies in different bars from 7·6 to 54·0 mm.

§ 100. **Photo-elastic Investigations on Stress Distribution.**—A considerable amount of experimental work has been carried out by Prof. Coker[2] in order to determine the stress distribution in various shapes of bars and beams. The method he adopts in all cases is to determine the direction of the lines of principal stress by observation on transparent models illuminated by plane polarised light.

Plane polarised light is split up into two rays by various transparent materials when they are under stress. These rays of white light recombine to give colour bands which vary in different parts of the material according to the nature of the stress. The colours given by a tension test-piece under known intensities of stress are used for determining the difference between the principal stresses in places where there are varying stresses. Dark patches show places of equal principal stresses or of zero stress.

The values of the two principal stresses are separated by measuring the lateral strains at the same points.

For his experiments Prof. Coker uses nitro-cellulose sheet which has a low modulus of elasticity and therefore gives com-

paratively large strains. Stress distribution by this method can be measured to an accuracy of ± 3 per cent.

In a series of experiments on tensile test-pieces having a straight parallel portion connected by arcs of circles of various radii with the ends, Prof. Coker finds a great concentration of stress near the enlarged ends. With a uniform stress of 1180 lbs. per square inch along the gauge length, there is a maximum stress of 1480 lbs. per square inch with a $\frac{1}{4}$ inch radius and 1890 lbs. per square inch when the radius is reduced to $\frac{1}{16}$ inch (Table XXXII).

TABLE XXXII.

TENSION SPECIMEN 0·4600 INCH × 0·1812 INCH, UNDER STRESS OF 1180 LBS. PER SQUARE INCH WITH ENLARGED ENDS 0·9316 INCH WIDE.

Radius of Connecting Curve.	$\frac{1}{2}$ Inch.	$\frac{1}{4}$ Inch.	$\frac{1}{16}$ Inch.
Maximum stress in lbs. per sq. in. . .	1480	1725	1890
Per cent. increase of stress . . .	23·4	43·8	57·5

These experiments show clearly the great importance of large radii for connecting the gauge length to the enlarged ends when using brittle materials (with ductile materials an equilisation of stress takes place before fracture). From the photographs in this series of tests Coker shows that, apart from consideration of increased local stress, the test-bar with the sharpest re-entrant angle has the greatest length in pure tension. From the results given in Table XXXIII it is possible to determine the fractional part of the length of any test-bar which is under pure tension in terms of the length between the shoulders and the breadth of the parallel portion of the bar.

If b = breadth of the parallel portion of the test-piece
L = the length between the shoulders

$$K = \frac{\text{length under pure tension}}{\text{length between the shoulders}}$$

= fractional part of the length under pure tension

$$K = \frac{L - 1{\cdot}78b}{L} \text{ where radius} = \tfrac{1}{4} \text{ inch}$$

$$L(K - 1) = 1{\cdot}78b.$$

TABLE XXXIII.

Radius of Connecting Curves . . . . Radius in Terms of Minimum Breadth . .	$\frac{1}{2}$ in. $0{\cdot}544b$	$\frac{1}{4}$ in. $0{\cdot}272b$	$\frac{1}{8}$ in. $0{\cdot}130b$	0 —
Maximum distance in inches between the shoulders for which pure tension is not possible	0·82	0·60	0·46	0·42
In terms of the breadth (b) . . .	$1{\cdot}78b$	$1{\cdot}30b$	$1{\cdot}00b$	$0{\cdot}915b$

Coker uses the same method to investigate the effect of surface scratches on tensile test-pieces or beams. He finds that even with a mean stress of one-third of the yield stress signs of overstress can be observed at sharp corners and scratches, and if the load is an alternating one these indications gradually penetrate further into the test-piece. If the material is a ductile one cracks are apparent along the planes of maximum shear stress, i.e. along planes inclined at 45° to the line of pull.

A groove of the form used for the Izod test (§ 198), e.g. with straight sides at 45° and a root radius of one-eighth of the depth, give a maximum stress at the apex of the notch of more than five times the mean stress. With sharper notches the effect is still more marked.

§ 101. **Strength of Screwed Bolts.**—The results of some tensile tests on four different kinds of screw threads, made by the authors, are given in Table XXXIV.

The threads selected were :—

(i) British Standard Fine.

(ii) British Standard Whitworth.

(iii) Sellers Thread.

(iv) U.S.A. 60° Sharp V Thread.

Four materials were used ranging in ultimate stress from 24·0 to 52·7 tons per square inch. The bolts were $\frac{5}{8}$ inch diameter and were all machined from $1\frac{1}{4}$ inch diameter bar.

From the results in Table XXXIV it is seen that, for steel up to 40 tons per square inch, the strength (per square inch of section taken at the bottom of the thread) is greater for the bolts than for the plain bar, but that for the 53 ton steel the bolts, with the exception of those screwed with B.S.W. thread, are weaker than the plain bar.

Martens [3] has carried out similar tests on $\frac{1}{2}$ inch and 1 inch bolts using steels of 27·7 and 23·9 tons per square inch respectively. His conclusions are as follows :—

(1) Screw threads subjected to plain tension are stronger than

plain bars of the same net cross-sectional area, the excess of strength being approximately 14 per cent.

TABLE XXXIV.

TENSILE TESTS ON SCREW BOLTS. ($\frac{3}{4}$ INCH DIAMETER.)

	Material. 1.	Material. 2.	Material. 3.	Material. 4.
Tensile test on material.				
Yield stress	15·6	17·6	23·5	25·6
Ultimate stress	24·0	29·5	40·3	52·7
Per cent. of extension, $L/\sqrt{A} = 4$	41·0	39·0	28·0	19·0
British Standard fine thread (root diam. = 0·5335 in.).				
Yield stress	17·8	20·1	24·7	26·7
Ultimate stress	26·3	33·8	46·6	48·6
British Standard Whitworth (root diam. = 0·5086 in.).				
Yield stress	18·0	20·4	26·0	26·6
Ultimate stress	27·0	34·0	45·9	54·0
Sellers thread (root diam. = 0·5069 in.).				
Yield stress	19·0	21·0	25·5	26·6
Ultimate stress	26·8	34·7	44·9	51·0
U.S.A. sharp 60° V thread (root diam. = 0·495 in.).				
Yield stress	17·7	21·3	26·5	25·6
Ultimate stress	28·2	35·3	47·1	47·1

Note.—(1) Stresses are given in tons per square inch.
(2) For tests on threads, the area for calculating the stress is taken as that at the bottom of the thread.

(2) There is no marked difference in the ultimate strength with different forms of threads—the sharp thread is slightly stronger than the others.

(3) Under repeated loads and impact it is probable that the sharp V threads would develop cracks quicker than the other forms and that the Whitworth thread would be the last to show this weakness either with repeated loads using soft material or static loads with high carbon steel.

The two sets of experiments by different experimenters, described above, are in agreement. It will be seen that Marten's supposition with regard to the superiority of the B.S.W. thread with high carbon steels under static load is shown by the authors' tests to be correct.

With regard to Martens' statement of the probable weakness of sharp V threads under impact, some tests by the authors also confirms this conclusion. The tests, of which the results are given in Table XXXV, were made on 1-inch bolts and broken by a single blow, the energy absorbed in fracture being measured. It will be noted from the table that the sharp V bolts are the weakest of those tested and the British Standard Threads are the strongest.

TABLE XXXV.

IMPACT TESTS ON SCREW THREADS. (1 INCH DIAMETER.)

Kind of Thread.	Diameter at Bottom of Thread. Inches.	Ft.-lbs. Absorbed in Fracture.	Per Cent. of the Energy Taken by the B.S.F.
British Standard fine . .	0·872	2275	100
Sellers thread (chasing tool)	0·838	1921	84
Sellers thread (single pointed tool) . . .	0·835	1888	83
British Standard Whitworth thread . . .	0·840	2003	88
U.S.A. sharp V thread .	0·780	1599	70

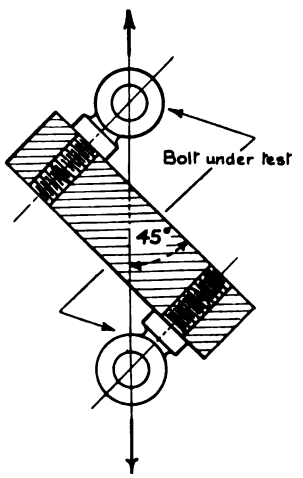


FIG. 111A.—Lifting bolts tested with a 45° pull.

§ 102. **Strength of Lifting Bolts.**—If the weight to be taken by lifting bolts is not adjusted so that the pull on the bolts is axial, the load which can be carried is considerably reduced.

A set of tests were carried out by the authors on several sizes of bolts. Some were tested with the loading axial and others were arranged in pairs, as indicated in Fig. 111A, in order to give a pull at 45° to the axis. The strengths under the latter conditions were found to be only about one-fourth of those obtained by axial loading. The results are given in Table XXXVI.

§ 103. **Influence of Time on Test Results.**—General experience shows that elongation and contraction of area are increased by very rapid loading but that, within the ordinary limits

of time occupied by a tensile test (to fracture) of most materials, the rate of loading does not appear to have any effect on these results. The results from various experimenters, however, are not quite consistent.

TABLE XXXVI.

TENSILE STRENGTH OF LIFTING BOLTS.

Diameter of Thread. British Standard Whitworth.	Tested Axially. Load in Tons.	Tested at 45° to Axis. Load in Tons.
2 ins.	57·5	12·3
1 in.	19·6	4·6
¾ in.	11·8	3·8
½ in.	6·6	1·72

(i) **Effect of Very Rapid Loading.**—Maitland [4] found that steel, broken in impact, gave 74 per cent. more elongation than the same material broken in the static tensile testing machine.

Blount, Kirkaldy and Sankey [5] concluded that the impact tensile test gave the ductility in the same terms as the static tensile test but always with higher numerical values.

On the other hand Lebasteur [6] was unable to find this difference with steel bars. His tests gave fractures which were the same in appearance in the two cases and the elongations of similar bars were also nearly identical.

(ii) **Effect of Variations of Slow Rates of Loading.**—Bauschinger [7] carried out a fairly complete set of experiments under slow rates of loading and showed that :—

(*a*) The effect on the elongation of altering the rate of loading varied according to the material employed. With cast iron the effect was negligible, while with steel, wrought iron, copper, bronze and brass it was so slight that it was masked by differences in the quality of the test-bars. For lead and tin there was a marked increase in the extension with time.

(*b*) The ultimate stress was in some cases greater when the extension was fast than when it was slow.

Tests on iron and steel given by the Commission des Méthodes d'Essai des Matériaux [8] show very little difference in the ultimate extension or the ultimate stress whether carried out in a few seconds or many minutes.

Bottomley,[9] however, when experimenting with soft iron wire, found that, generally, the contraction of area and local contraction were less if the loads were applied more slowly. His researches

included a determination of the effect of time on the breaking load of soft iron wire. He found that the wire, if loaded to just below the ordinary breaking load, increased in strength according to the time the wire was under this initial load.

A summary of the results are given in Table XXXVII.

TABLE XXXVII.

Time the Load was Allowed to Remain on the Wire.	Maximum Load to Fracture. Lbs.	Elongation. Per Cent.
Ordinary test in 10 minutes . .	43·5 to 46	22 to 17
24 hours at 43 lbs. . . .	49·25	15
84 hours at 43 lbs. . . .	51·5	14·4
2 months gradual loading from 40 lbs.	57·25	—

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[1] Stromeyer, "Proc. Inst. Civ. Eng.," 1884, Vol. LXXVI, p. 142.
[2] Coker, "Tension Tests of Materials," "Engineering," Jan. 7th, 1921.
[3] Martens, "Zeits. Vereines Deutsch. Ing.," April 27th, 1896.
[4] Maitland, "Treatment of Gun Steel," "Inst. Civ. Eng. Proc.," Vol. LXXXIX, p. 120.
[5] Blount, Kirkaldy and Sankey, "Comparison of Methods of Testing Steel," "Inst. Mech. Eng. Proc.," May 27th, 1910.
[6] Lebasteur, "Ann. des ponts et Chaussees," 1890.
[7] Bauschinger, "Inst. Civ. Eng. Proc.," Vol. CVII, p. 434.
[8] "Méthodes d'Essai des Matériaux," Vol. I, p. 344.
[9] Bottomley, Article "Elasticity" in the "Encyclopædia Britannica".

CHAPTER XI.

MEASURING INSTRUMENTS FOR THE DETERMINATION OF THE ELASTIC CONSTANTS OF MATERIALS.

§ 104. IN order to obtain information as to the elastic constants of materials it is necessary to measure deformations while these materials are being strained elastically.

In commercial testing, where a measure of the ductility only is required, the final amount of deformation is all that is necessary. In a tensile test with a standard 2-inch gauge length and cross-sectional area of 0·25 square inch the total elongation may be 0·50 inch, and as this can be measured by the aid of dividers to the nearest $\frac{1}{100}$ inch the accuracy of reading is 2 per cent.

Using the same size of test-piece and gauge length the extension at the elastic limit is of the order of 0·002 inch, so that for the same percentage accuracy the measurement must be correct to 0·00004 inch; the smallness of this extension can be realised when it is considered that the thickness of a piece of cigarette paper is about 0·001 inch. With the best types of mirror extensometer alterations of length can be accurately measured to $\frac{1}{10}$th of this amount, i.e. 0·000004 inch.

§ 105. **Extensometers.**—In any type of strain measuring apparatus there are certain general principles which it is advisable should be fulfilled.

(1) If changes in length of the axis of the test-bar are to be determined, measurements should be taken on opposite sides of the specimen. Unwin [1] has shown that, if this condition is not satisfied, initial curvature of the bar will cause serious errors in the results, but "if the mean of measurements taken at points symmetrically placed on either side of the bar is adopted, the error due to curvature is nearly eliminated, the lengthening of the distance of one side being compensated by shortening on the other".

(2) The apparatus should be directly attached to the test-piece at the gauge points only, and after the initial setting it

should not be necessary to handle it during the course of the experiment.

(3) The instrument should be as light as possible and designed so as to be rapidly attached to or detached from the test-piece without interfering with the application of the load. It is advisable that, if possible, it should be self-contained.

(4) The instrument should be arranged so that its accuracy can be determined by a calibrating device and the attachment to the test-piece should be such that the gauge length is capable of determination with sufficient accuracy.

(5) The mechanical or optical details and the relative positions of all the parts with respect to the axis of the specimen should be such that the "constant" of the instrument is the same throughout its range or that any errors which are involved are so small as to be of no importance.

(6) The zero of the instrument should be constant for the same conditions of test, thus if, after straining the test-piece, there is no permanent set the instrument should return to its initial position.

Extensions are measured in five different ways :—

(1) With a micrometer screw.
(2) By an indicating dial.
(3) With a microscope.
(4) By a multiplying lever (mechanical magnification).
(5) By optical magnification.

With methods (1), (2) and (3) the deformations are ascertained with little or no magnification while with instruments employing methods (4) and (5) the strains are considerably magnified before the measurements are made. Some extensometers use a combination of (4) or (5) with (1), (2), or (3).

§ 106. **Micrometer Screw Extensometers.**—These instruments consist of two clamps placed on the test-bar at a distance apart which is equal to the gauge length. The movement of one clamp relatively to the other, as the load is applied, is measured by the reading of one or more micrometer screws fixed to one clamp and brought into contact with the other. The accuracy of the instrument depends on :—

(*a*) The uniformity of the pitch of the micrometer screw.
(*b*) The constancy of the pressure at the point of contact.
(*c*) The care with which the micrometer screw is operated, because the instrument has to be touched by hand many times during the experiment. Care should be observed in order to

ensure that the couple applied by the fingers is perpendicular to the axis of the screw.

Mic ometer screw extensometers are largely used in the U.S.A. and give satisfactory results when used with great care. The principal makes of instrument are divided into two sections according as to whether they have one or two micrometers.

§ 107. **Double Micrometer Screw Instruments.**—(1) *Prof.*

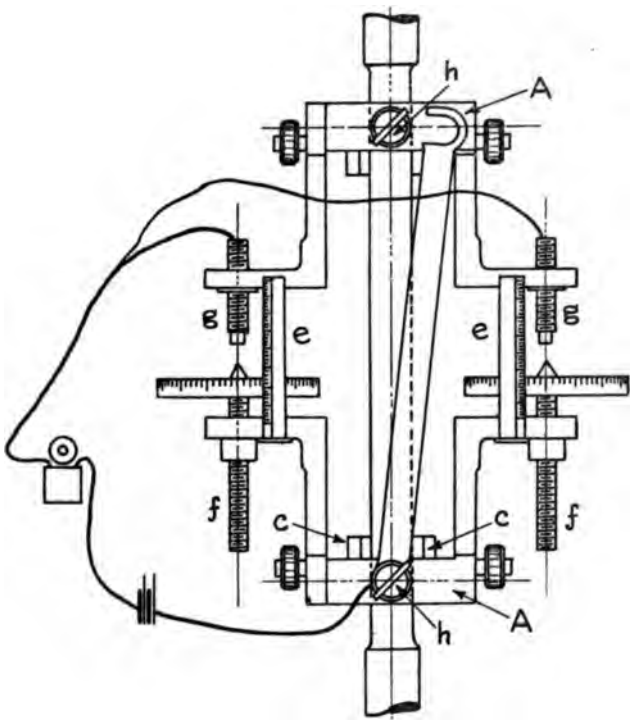

FIG. 112.—Henning's extensometer.

R. H. Thurston's[2] *Extensometer* (1875).—This was the first instrument in which two micrometer screws were used, one placed on each side of the axis of the test-piece, and in which electric contact was employed in order to eliminate errors due to variation of pressure.

(2) *Henning's*[3] *Micrometer Extensometer.*—This instrument is shown in Fig. 112. Two frames (AA) grip the test-piece by two steel points (*hh*) and two knife edges (*cc*). The lower

frame carries two micrometers and the upper frame is provided with a pair of plugs (*gg*) which are in line with the micrometers. As the distance between the frames increases with application of the load the ends of the screws (*ff*) are brought in contact with the plugs (*gg*). The contact is indicated by ringing an electric bell by a weak electric current or, owing to the uncertainty of bell mechanisms, telephone receivers are sometimes substituted. The extension is read on vertical scales (*ee*) and the graduations of the micrometer heads.

The instrument registers to $\frac{1}{10.000}$th part of an inch and can be used on either round, flat or square specimens. In order to attach the extensometer to the test-piece the frames (AA) are opened. Bars are used for setting the frames (AA) at the correct distance apart but they are removed while the test is in progress. An instrument of this type is supplied by Messrs. Tinius Olsen Testing Machine Co., Philadelphia, under the name of The Olsen Standard Duplex Micrometer Extensometer.

(3) *The extensometer* invented by C. A. Marshall of the Cambria Iron Company differs from Henning's in three small details. The adjusting bars (Fig. 112) are omitted and the knife edges (*cc*) are replaced by a spring and roller attachment which, in connection with a spirit level, assists in the accuracy of the adjustment. The micrometer screws are placed nearer the lower frame than in the Henning extensometer.

(4) *The Yale Extensometer*[4] is a simplification of the Marshall apparatus. The spring rollers are omitted and a gauge bar introduced to keep the clamps parallel, bring the points of measurement opposite and gauge the length. The gauge bars are made of different lengths and are removed before beginning to strain the specimen. It reads to ten-thousandths of an inch by micrometer screw.

§ 108. **Single Micrometer Screw Instrument.**—*Unwin's*[5] *Screw Extensometer.*—This instrument is shown diagrammatically in Fig. 113. The two frames are clamped to the test-piece at points on a plane passing through its axis by set screws (*a* and *b*). The lower frame carries the micrometer screw (*e*), on the hardened point of which the upper frame rests. Provided that the frames are at right angles to the axis, the micrometer screw gives the variations in the length between the two points of support on the test-piece. To set the frames normal to the axis of the test-bar, levels (*c*, *f*) are attached to them. Level (*c*) on the lower frame is adjusted by the screw (*d*), while the upper frame is set level by means of the micrometer screw (*e*). The pressure

on the micrometer screw is thus constant and equal to the weight of the upper frame.

§ 109. **Single Micrometer Screw Combined with a Multiplying Lever.**—(1) *Garratt's*[6] *Extensometer.*—In this instrument (shown diagrammatically in Fig. 114) there is a mechanical magnification of two, combined with measurement by means of a single micrometer screw. Two pairs of steel plates (B and C) are attached to the test-piece by screws (EE) and pivoted

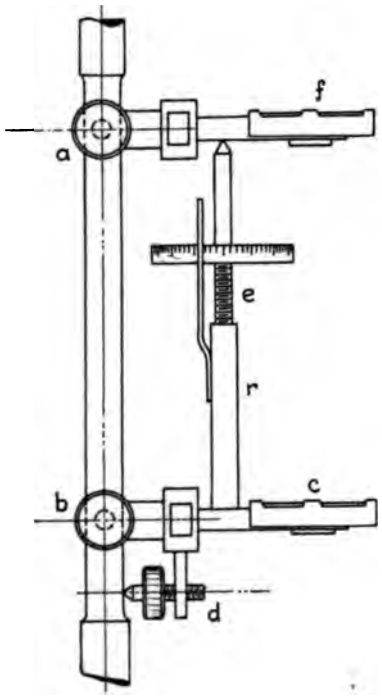

FIG. 113.—Unwin's micrometer screw extensometer.

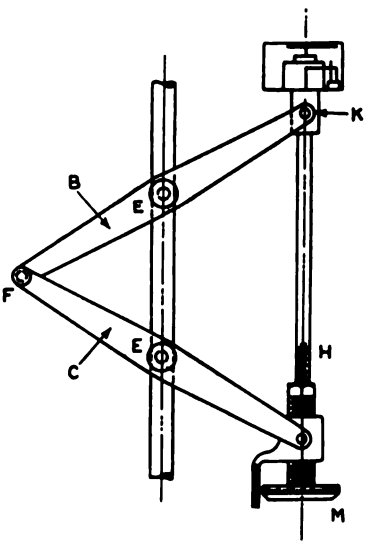

FIG. 114.—Garratt's extensometer.

together at F. The micrometer (M) is pivoted to the lower plates and carries a spindle (H) which passes through a guide (K) pivoted to the upper plates. The spindle carries a hardened pin on its upper end and, when the test-piece extends, this pin, which forms part of an aneroid barometer, moves the aneroid needle. Half of the amount which the micrometer has to be moved to bring the needle to its original position is a measure of the extension.

(2) *Riehlé's Improved Extensometer*, supplied by Messrs. Riehlé Bros. Testing Machine Co., reads the average stretch from two side of the test-bar with one micrometer screw. The arrangement is shown diagrammatically in Fig. 115. The two frames (A and B) are each fixed axially to the test-piece by two hardened steel-pointed thumb screws (SS). The left-hand rod (R) is rigidly joined to the lower frame (B) and is pivoted to the upper

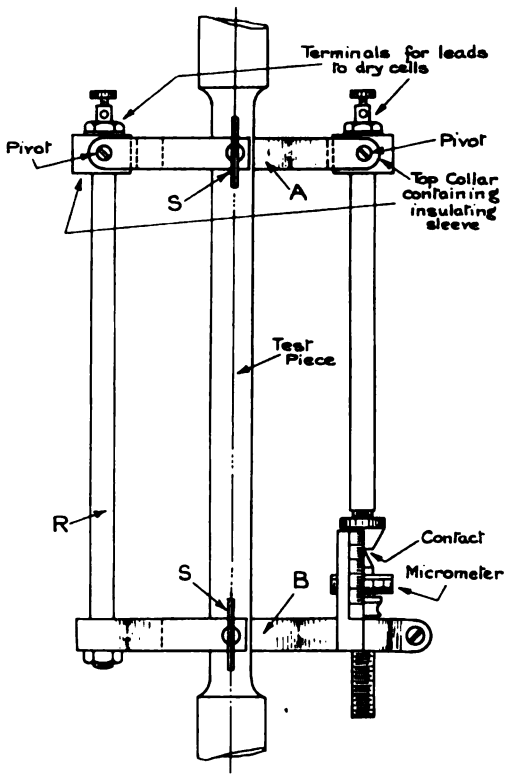

FIG. 115.—Riehlé's improved extensometer.

one (A). The right-hand rod swings from a pivot in the upper frame over the micrometer screw in the lower one. The rods are equidistant from the points of attachment to the specimen so that when elongation occurs the right hand swinging rod moves away from the micrometer TWICE THE AMOUNT OF THE ELONGATION. This extensometer can be used on gauge lengths from 2 inches upwards by having sets of rods for those gauge lengths which

are required. Elongations of 0·0001 inch can be easily read and electric contacts can be employed with this instrument.

(3) *The Cambridge Extensometer* (Fig. 116).—This simple and accurate extensometer is made by The Cambridge & Paul

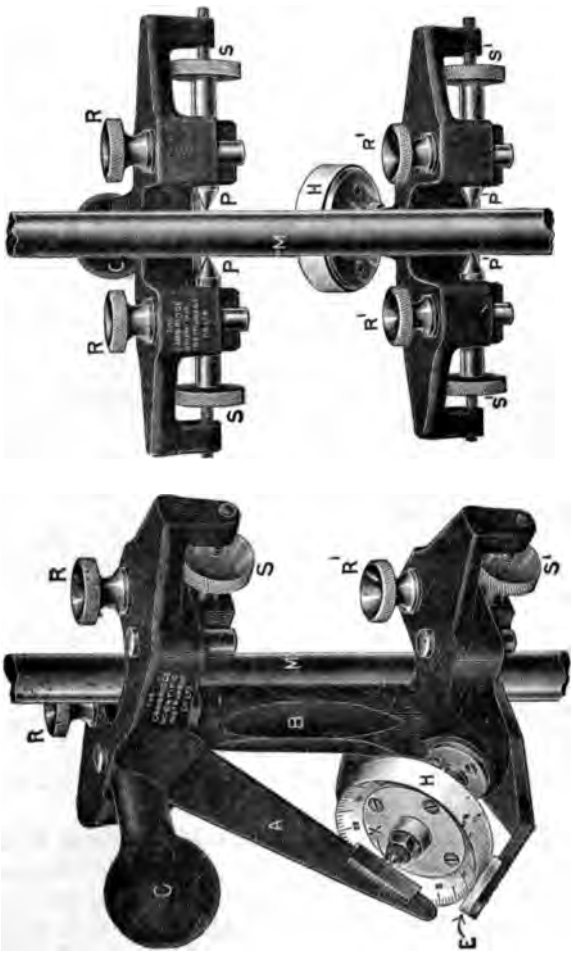

FIG. 116.—The Cambridge extensometer.

Instrument Co., Ltd., Cambridge, and is especially designed for use as a workshop instrument. It is composed of two separate frames each of which is attached to the test-bar (M) by hard steel conical points arranged in geometric slides so that, after the points are gently driven into the punch marks, they can be clamped in

position by the knurled heads (RR and R'R'). The lower frame carries a micrometer screw (H) and a vertical arm (B) at the top of which is a hardened steel knife edge about which the two frames work together. The micrometer screw is provided with a hardened steel point (X) over which a nickel-plated flexible steel tongue (A), forming a continuation of the upper frame, is carried. The tongue and frame form a lever magnifying the extensions of the test-piece by five.

In use the vibration of the flexible tongue takes the place of the electric contact, in the instruments previously described, as a delicate means of setting the micrometer screw. The steel tongue is vibrated and the screw turned until the point (X) just touches the hardened knife edge of the tongue as it vibrates. Readings can be repeated by this means to 0·001 mm. under ordinary conditions of test. The standard instrument is suitable for specimens up to $\frac{3}{4}$ inch diameter on a gauge length of 4 inches or 2 inches.

§ 110. **Indicating Dial Instruments.**—This type of instrument consists of one or more calibrated dials with pointers on nicely mounted spindles. These take the place of the micrometer screws in the previous class of extensometers and are self indicating for large or small deformations. They are generally used in conjunction with some form of lever magnification.

Messrs. T. Olsen Testing Machine Co. supply a dial extensometer of exactly the same form as Henning's extensometer (§ 107), except that dials and sliding rods replace the micrometer screws. The sliding rods are attached to the lower frame in place of the micrometer screws, and spindles, carrying drums and pointers, are fixed to the upper frame with their axes horizontal. These take the place of the plugs (*gg*, Fig. 112). The friction of the sliding rods against the small drums (1 inch in circumference) cause the latter to rotate. This also rotates the spindles and pointers round calibrated discs.

§ 111. **Dial Extensometers with Mechanical Magnification.**—(i) *University of Wisconsin Wire-wound Extensometer.*[7]—This has one dial, attached to the upper frame, which is operated by a wire arranged to transmit twice the extension of the test-piece to the dial drum.

(ii) *Hurst-Tomlinson Extensometer* (*Combined Lever and Dial*) (Fig. 117).—This instrument has been especially designed for use on the standard test-piece (0·564 inch diameter and 2 inches gauge length), it can be used, however, on specimens up to 1 inch in diameter. The gauge length of 2 inches is not adjustable, but

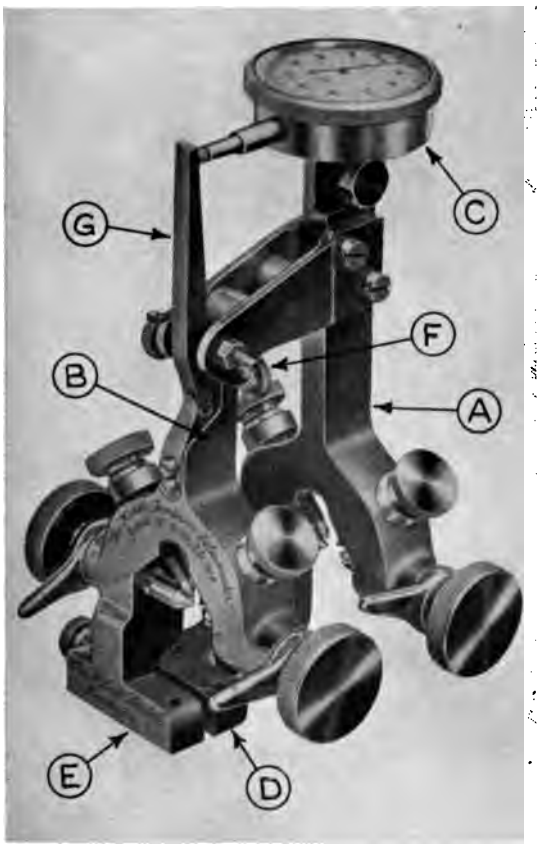

FIG. 117.—Hurst-Tomlinson extensometer.

[*To face p.* 164.

the instrument can be attached to specimens of greater length than this if required. It is provided with two forked levers (A and B), fitted at the fork with pointed clamping screws which, when tightened on to the test-piece, form the pivots of the levers.

The dial indicator (C) is attached to one end of the upper lever, and the other end, beyond the test-piece, has a stout vertical lug (D) extending downwards from one extremity of the fork nearly to the level of the lower lever. Here the lug bends inwards and one arm (E) of the fork of the lower lever extends inwards in the same way.

The two levers are connected by a short length of piano wire which lies in the central vertical plane of the two levers.

This forms an elastic hinge so that as the test-piece stretches the free ends of the levers open away from one another.

This method of connecting the levers also permits the test-piece to straighten out slightly under the load, if originally slightly bent, without straining the extensometer.

The lower lever is shorter than the upper one and it carries at the free end a short vertical screw (F) with a large milled head.

The end of the screw is rounded and polished, and bears on the end of the shorter arm of a third lever (G) which is attached by a short length of flexible steel ribbon to a bracket which is screwed and dowelled to the upper main lever. The end of the longer arm of this third lever bears upwards on the end of the plunger of the dial indicator.

The system of levers is proportioned so that the movement transmitted to the indicator is ten times the extension of the test-piece.

By turning the milled head of the screw (F) the dial indicator can be brought to zero before the load is applied, a light spring maintains the end of the small lever in contact with the point of the screw. While the extensometer is being attached it is necessary for the two main levers to be rigidly locked with the axis of the clamping points parallel and at a distance of two inches apart.

This is accomplished by inserting two locking pins, one of which constrains the axes to be parallel while the other fixes the distance between them.

The first pin is placed in the same horizontal plane as the wire hinge and its axis intercepts the centre of the wire so that the insertion of this pin leaves the levers only one degree of freedom.

The second pin correctly fixes the relative positions of the two levers.

In order to ensure that the clamping points shall grip the test-piece along a diameter and not along a shorter chord two screws are placed in the forked part of each lever inclined at about 45°.

The axes of these screws intercept the axis of the test-piece, and the ends are rounded to bear at points on the test-piece.

The usual diameter of the reduced part of the test-piece is 0·564 inch, which gives a cross-sectional area of 0·25 square inch, and the length of the screws is such that when just tight the ends are 0·282 inch away from the vertical plane through the clamping points.

When attaching the extensometer it is simply held up against the test-piece bearing on the ends of the four screws and the clamping screws are tightened and the points pierce the test-piece along two diameters. The extensometer is thus a self-contained marking-out jig. As soon as the instrument is fixed to the test-piece the four screws are just slightly slackened so that they are just clear while the test is being made.

One division on the indicator corresponds to an extension of 0·0001 inch and, by estimating, the extension can be readily measured to the nearest 0·00002 inch. This instrument is made by Charles W. Cook, Ltd., Manchester.

(iii) *Riehlé Dial Extensometer.*—A similar type of dial extensometer is supplied by Messrs. Riehlé Bros. Testing Machine Co. The instrument itself is not quite so elaborate and requires a special marking-off block which forms part of the outfit.

§ 112. **Microscope Reading Extensometers (Cathetometers).**—With this type of instrument the distance between fine scratches on the test-piece is measured by sighting with a microscope on the two scratches and reading off the distance that the microscope has been moved along the slide to which it is fixed. The determination of elongations by this method is a lengthy process, and except for special purposes it has been abandoned.

Fig. 118 shows an arrangement of two microscopes which is convenient for measuring the extensions of stranded cables. Microscope A has ordinary cross wires, while microscope B is fitted with a micrometer eye-piece. Both instruments are attached to a bar (C) which can be moved vertically by the screw (D). Both microscopes are focussed on scratches on the test-piece and the load applied. By means of the screw (D) the cross wire of the top microscope (A) is made to coincide again with the top scratch while the adjustable cross wire is moved in the second microscope to the new position of the bottom scratch. The

movement of this cross wire in the calibrated micrometer eye-piece gives the extension.

§ 113. **Combined Microscope and Lever Extensometer.**—*Ewing Extensometer.*[8]—This instrument has been used for a great deal of the scientific work in this country. It is shown diagrammatically in Fig. 119, and in its latest form in Fig. 120. The two

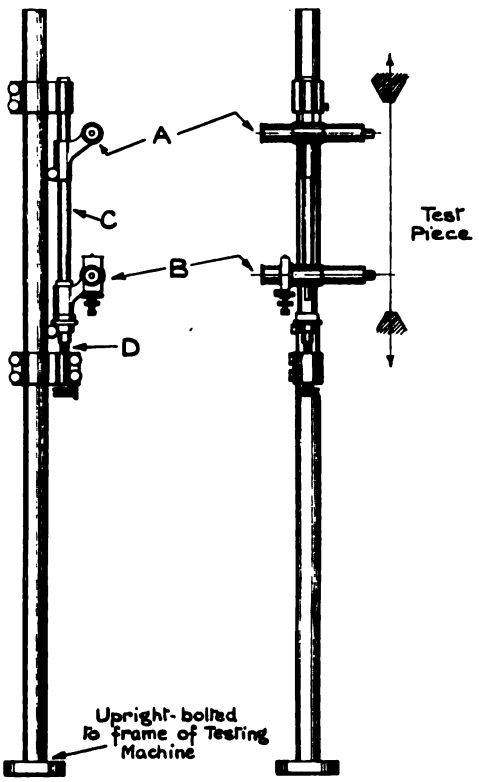

FIG. 118.—Microscope reading extensometer.

clips (B and C) are each attached to the test-piece (A) by two pointed screws. Clip B carries the vertical projection B_1 (Fig. 119) terminating in a rounded point (P) which engages with a conical recess in C. The pieces (B and B_1) are joined to one another in such a way that the test-piece may twist a little without affecting the engagement of P with C. When the test-piece extends, P serves as a fulcrum for the clip C, and point Q is displaced

through a distance equal to twice the extension. This displacement is measured by a microscope attached to B, sighting on a mark on the rod (R) hanging from the point (Q) on the upper

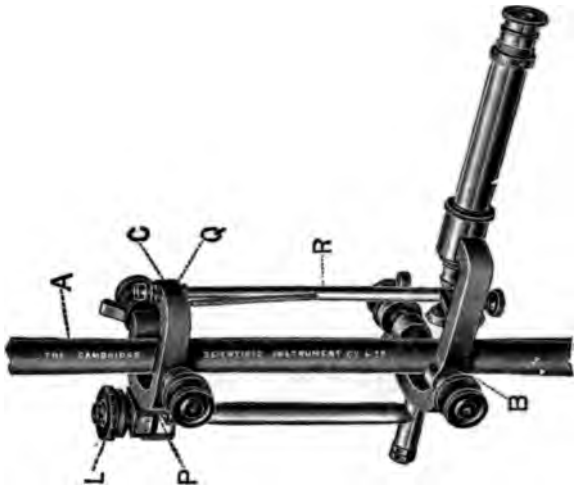

FIG. 120.—3/16 full size.

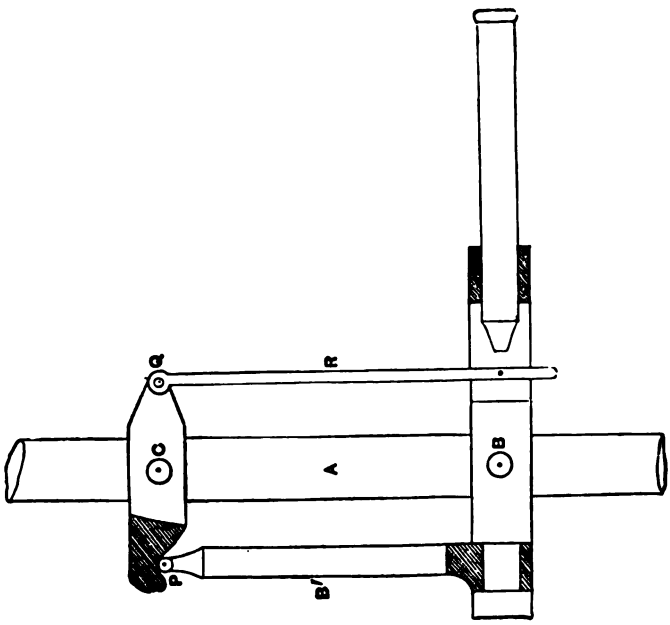

FIG. 119.—Diagrammatic view.

clip. The readings are taken from a micrometer scale in the eye-piece of the microscope. The screw (L, Fig. 120) serves to bring the sighted mark to a convenient point on the micrometer scale, and also determines the scale readings which can be estimated to 0·00002 inch. A clamping bar is added by which the clips (B and C) are held at the correct distance when fixing them on the test-piece. This extensometer is made by Messrs. The Cambridge & Paul Instrument Company for gauge lengths of 2 and 8 inches and 10 and 20 centimetres.

§ 114. **Multiplying Lever Extensometers (Mechanical Magnification).**—(i) Kennedy[9] designed a simple lever (leverage 100 to 1) extensometer clipped to the test-bar at two points.

(ii) *Martens'*[10] *Lever Extensometer* is a modification of the Kennedy instrument and is arranged to take simultaneous readings on two opposite sides of the specimen. It is shown diagrammatically in Fig. 121 and consists of two clips (DD) carrying the graduated scales (CC) and held on opposite sides of the specimen by a spring (S). Diamond-shaped pieces (AA), to which the arms (BB) are attached, are pivoted in shallow seats formed in the clips (DD). With a magnification of fifty, readings can easily be made to 0·002 mm.

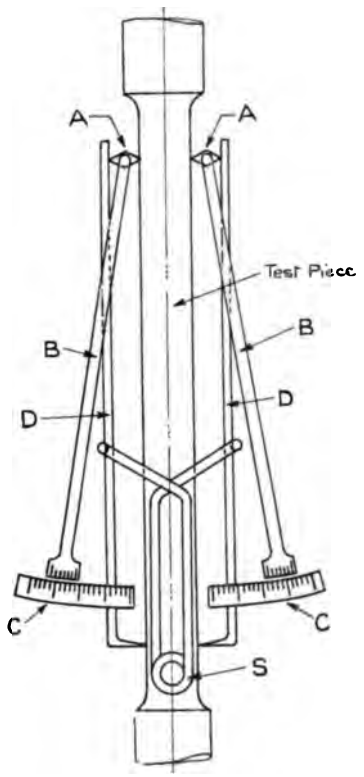

FIG. 121.—Martens' lever extensometer.

(iii) *Kennedy's*[11] *Horizontal Extensometer* is gripped on the bar at four points in an axial plane and consists of two frames, one fixed to each gauge mark, which rest on each other over the points of attachment to the test-bar. A light pointer is provided with two steel points, one resting on each frame. When the test-bar elongates the two points move relatively to each other in an axial direction and this movement is magnified by the end

of the pointer which travels over a scale carried by a rod attached to one of the frames.

Other instruments of this type have been designed by Stromeyer,[12] Goodman,[13] Wicksteed,[14] Ashcroft,[15] Col. W. H. Paine,[16] and Dupuy [17].

§ 115. **Optical Magnifying Extensometers.**—For greater accuracy than 0·00002 inch in measuring deformations some form of optical lever is generally employed in which the change of length of the test-piece is converted into rotary motion of a mirror which is observed by means of a telescope and scale. Some extensometers employ two mirrors in which readings are obtained from opposite sides of the test-bar, while in others the mean extension is measured by the reading from a single mirror.

(i) **Two-mirror Apparatus.**—(*a*) *Bauschinger's Instrument.*[18] —The introduction of mirror extensometers is principally due to

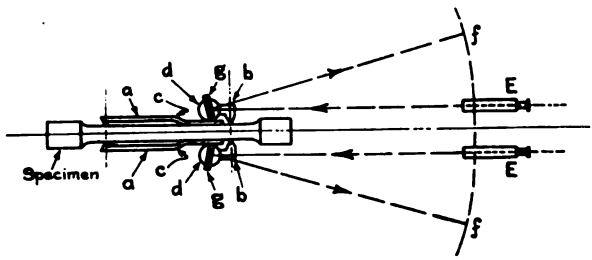

FIG. 122.—Bauschinger's mirror extensometer.

Bauschinger who designed the instrument shown in Fig. 122. Two clips (*aa* and *bb*) are pressed against the specimen : *cc* are light springs which press outwards against the rollers *dd*. These rollers, which are of caoutchouc, are carried by the clip (*bb*), and themselves carry the mirrors (*gg*). As the specimen extends the rollers rotate, and these rotations are measured by means of the telescopes (EE) and scales (*ff*). The results are recorded to 0·0001 mm.

(*b*) *Martens' Mirror Extensometer.*—This is an improvement of Bauschinger's instrument and is shown in Fig. 123. It is extremely accurate and sensitive and is most adaptable. In this arrangement the multiplying levers of Martens' lever extensometer (Fig. 121) are replaced by small mirrors (*mm*, Fig. 123) which are attached to the rhombic-shaped pieces of steel acting as fulcra, in such a way that the reflecting surface of each mirror is on the axis of the fulcrum. The two clips (*dd*) are held on

opposite sides of the specimen by a spring (*s*) which rests in grooves (*cc*). Each clip is pointed at one end which is gripped

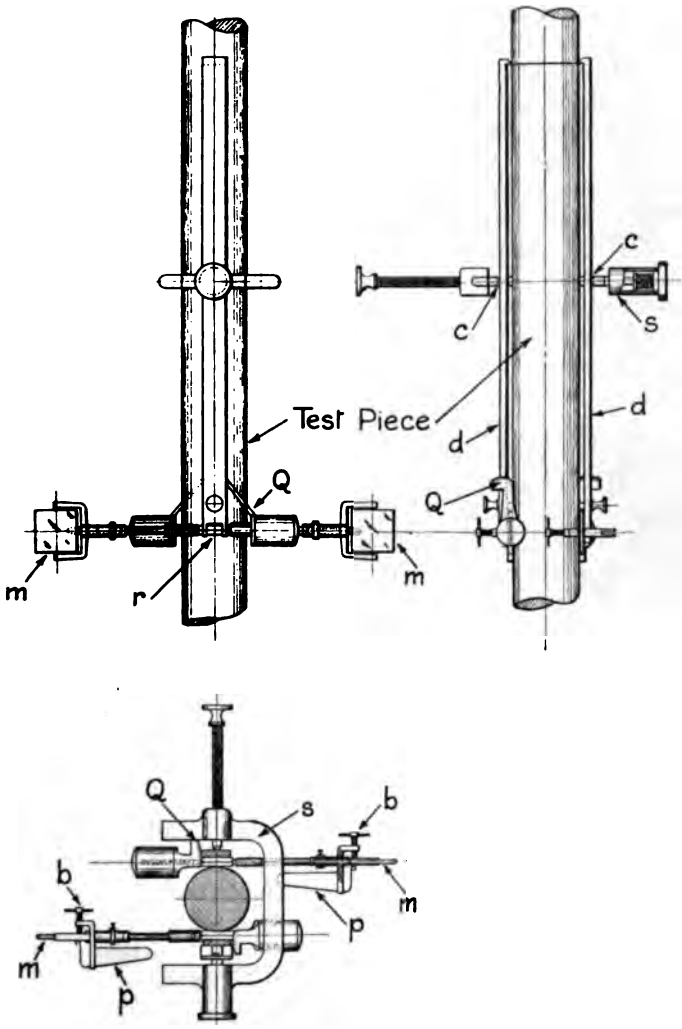

FIG. 123.—Martens' mirror extensometer.

directly on the test-bar, while the other end has the rhombic piece interposed between it and the bar. The mirror is mounted on a frame by means of pivots centred in small holes drilled in

the glass. In order to adjust the position of the mirror the frame is free to revolve on the axis of the rhomb. An adjusting screw (*b*) and spring (*p*) are placed on opposite sides of the mirror to control its position about an axis at right angles to that of the rhomb.

A pointer (Q) is attached to the rhomb and arranged so that, when it coincides with a mark on the clip (*d*), the instrument is set at the proper gauge length.

Extension of the test-piece rotates the rhombs, and the angular rotation is measured by a scale and telescopes as described for Bauschinger's extensometer. Two readings are necessary, one for each rhomb, and two telescopes are usually employed.

(*c*) *N.P.L. One-telescope Arrangement.*—At the N.P.L. a "one-telescope" arrangement has been in use for some years with complete success. This is shown in Fig. 124.

The telescope (T) is attached to a support (S). Immediately under the telescope, and attached to the same support, is a platform (P) whose height from the ground can be quickly adjusted. It can be locked in any position by a knurled-headed screw (A). The telescope arrangement is kept in contact with the platform by means of a spring, and their relative position in a horizontal plane can be accurately adjusted by means of the pivoted nut and screw (C).

The platform carries an illuminated scale (D), two fixed mirrors (M_1 and M_2) and two mirrors (N_1 and N_2) pivoted vertically so that their position can be altered by means of the screw and spring (E).

The illuminated scale is reflected from one of the "Martens" rotating mirrors on to the pivoted mirror N_1, and the angle of this is adjusted to bring the reflection into the telescope by means of the fixed mirror M_1. The other "Martens" mirror is made to reflect the illuminated scale on to the pivoted mirror N_2, and this is adjusted to bring the reflection into the same telescope. The difference between the lengths of the two rays is so small that the telescope can, at the same time, focus the scales reflected by each of the "Martens" rotating mirrors. The mirrors reflect "ghosts," and these are cut out by inserting a mask (Fig. 125) in the eye-piece of the telescope and by having

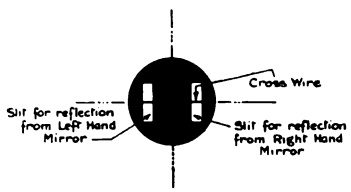

FIG. 125.—Mask in eye-piece of telescope of apparatus for mirror extensometers.

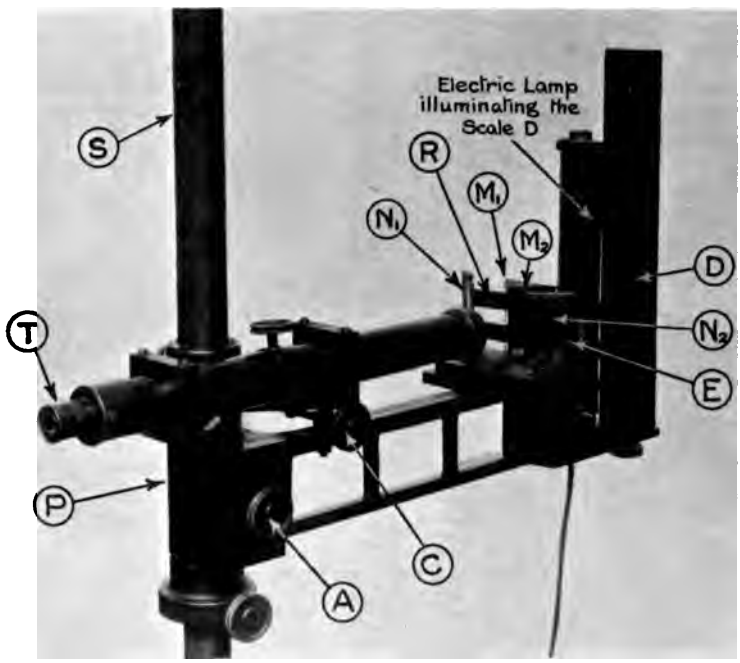

FIG. 124.—N.P.L. telescope arrangement for mirror extensometers.

[*To face p.* 172.

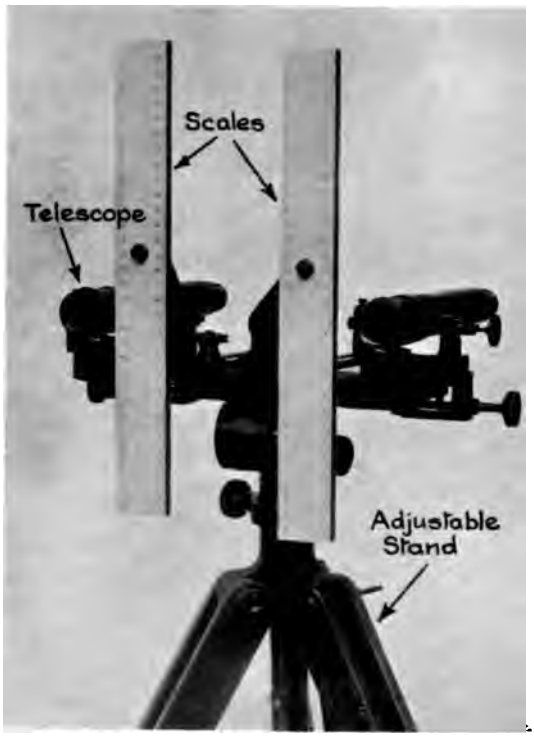

FIG. 126.—Amsler telescope arrangement for mirror extensometers.

[*See p.* 173.

FIG. 131.—Ewing compressometer for short blocks.

[*See p.* 177.
[*To face p.* 173.

adjustable brass shades (R, Fig. 124) fixed in between the mirrors on the platform and the extensometer.

The mirrors used must be absolutely flat and great care should be taken to see that they are not distorted when they are clamped in position.

(*d*) *Amsler's Two-telescope Arrangement.*—This apparatus is shown in Fig. 126, it is convenient to use, is easily adjusted and the scale divisions are clear and definite.

With both types of instrument, (*c*) and (*d*), the stands are first adjusted until the telescopes are horizontal and focussed on to the mirrors. The scales are then set at the correct distance from the mirrors—this is preferably done by means of a gauge made of such a length as to give a definite multiplication calculated from the measured width of the extensometer rhombs. The focal arrangements of the telescopes are then set at positions which, known from previous tests, will focus the scales when they are in the field of view. The scales are then brought into the correct position in this field by means of the adjusting screws on the extensometer mirrors.

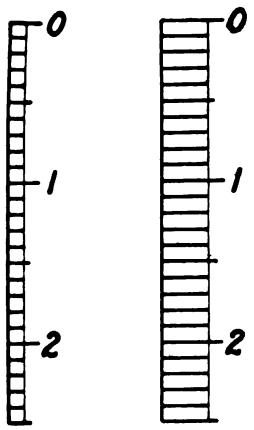

FIG. 127.—Properly proportioned scale. FIG. 128.—Incorrectly proportioned scale.

Finally, the extensometer mirrors are revolved until scale readings are obtained from the proper ends of the scale, that is to say, care should be taken to ensure that, as the test proceeds and the rhombs rotate, readings are always obtained on the scales. It will be noted that the two extensometer rhombs or mirrors rotate in opposite directions as the test-piece is strained.

A curved scale should be used but readings can be taken on a straight scale and a correction applied if the results are required of great accuracy. The scale is graduated in millimetres and readings of the scale can be estimated to 0·1 mm.

With scales for extensometers, as well as those for general use, fewer mistakes in observing are recorded if the lengths of the lines and the widths of the scale divisions are properly proportioned. Fig. 127 shows a scale which can be read accurately without undue eye strain. The widths of the scale divisions

are equal to the heights of the division lines. If the width is greater than about twice the height there is a likelihood of errors of observation. Fig. 128 gives an incorrectly proportioned scale.

If l = the width of the rhombs.
L = distance from the scale to the axis of the test-piece.
x = extension of the test-piece.
X = *sum of the readings* from the two Martens mirrors.

$$\frac{x}{X} = \frac{l}{4L}.$$

Usual values of l and L are 0·180 and 45·0 inches respectively. If X is measured in millimetres we have

$$x\,(\text{mm.}) = \frac{l \times X}{4 \times L} = \frac{0{\cdot}18 \times X}{4 \times 45} = 0{\cdot}001X.$$

By providing suitable clips this extensometer can be used on gauge lengths from one inch upwards and with test-pieces from 0·03 to 0·8 inch diameter.

An instrument using Martens' method, but of slightly different design to that shown in Fig. 123, is supplied by Messrs. Alfred J. Amsler & Co., Schaffhausen.

(*e*) *Westinghouse Wire-testing Extensometer.*—This instrument, designed by Lynch and Brace,[19] for extensometer tests on small sections, such as wire, ribbon, etc., is shown in Fig. 129. It consists of two clips (A_1 and A_2) fastened at one end to a slotted block (B) while the free ends carry hardened rollers (C_1 and C_2) which can turn in pivot bearings.

One end of the instrument is clamped to the test-piece between the spring (G) and the block (B), and the rollers (C_1 and C_2) are sprung apart to take the test-piece at the other end. Plane mirrors are attached to the rollers which are arranged so that a spot of light from a lamp (D) is reflected from the mirror C_1 to mirror C_2 and thence to the curved scale F.

With this extensometer increases of length of 0·00002 inch can be measured.

(ii) **Single-mirror Apparatus.**—*Morrow's Extensometer.*[20]—This instrument is a combination of Ewing's lever arrangement, for making the extensometer indicate the mean strain, with a mirror method of measuring that strain. It is shown diagrammatically in Fig. 130. The attachment to the test-piece (T) is by four set screws (AA and BB). AA serves as a fulcrum for the top annular ring C and, when the test-piece extends, the

movement between C and F (which is an extension of the bottom ring D) is approximately twice the extension. So far the principle is the same as that of the Ewing extensometer but,

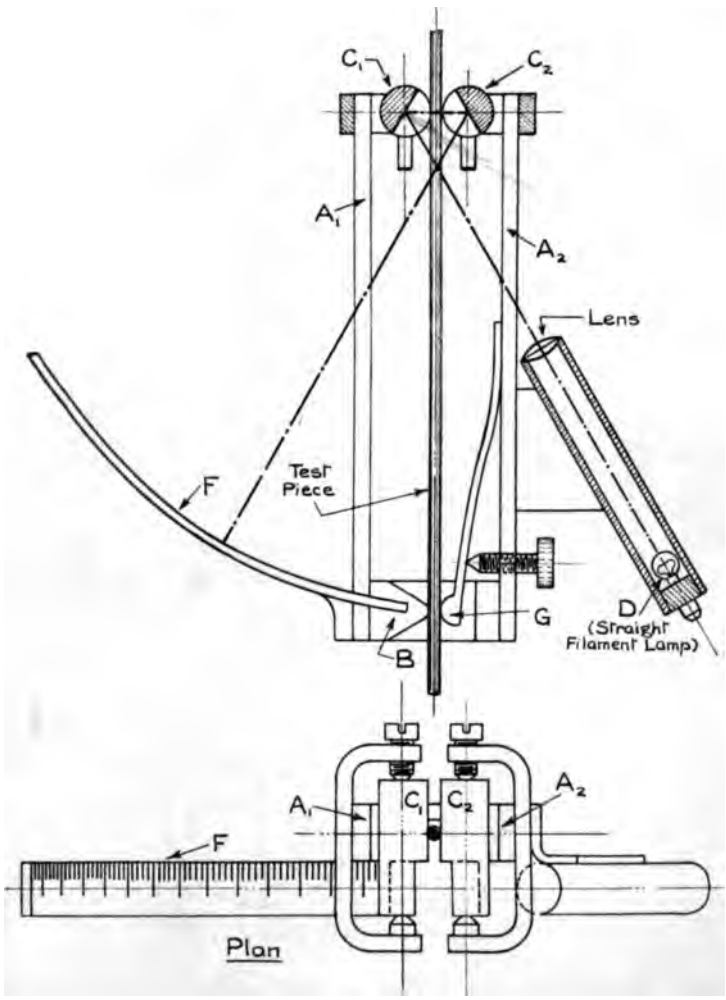

FIG. 129.—Westinghouse wire-testing extensometer.

whereas Ewing measures this extension by a micrometer microscope, Morrow uses a "Martens" rhomb (H) to which a mirror (N) is attached in a vertical position.

A second mirror (M) is permanently fixed to F. The images of the scale from both mirrors are seen side by side in the telescope An index mark is taken on the image of M for reading the movement of N. By this means allowance is made

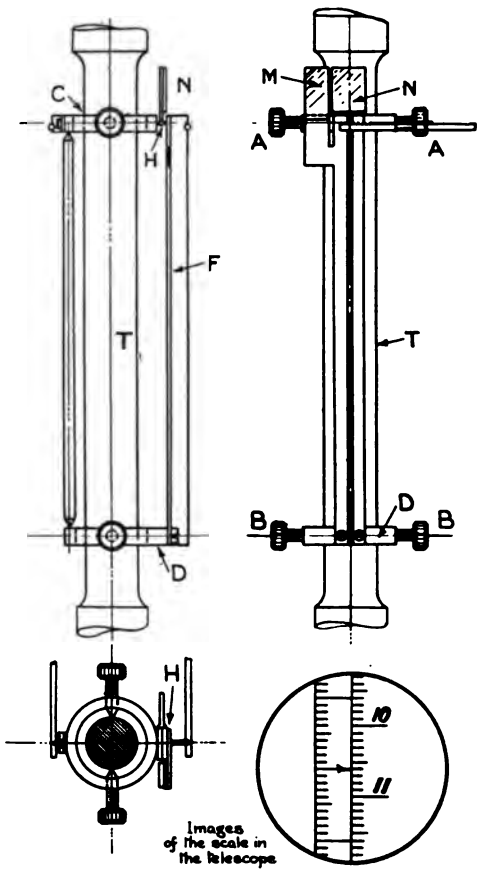

FIG. 130.—Morrow's extensometer.

for any movement of the test-piece and extensometer, as a whole, relative to the position of the telescope.

With the instrument as used by Morrow the extension of the specimen is obtained to the nearest $\frac{1}{120000}$ of an inch.

Other single-mirror extensometers have been designed by Unwin,[21] Martens,[22] and Hartig.[23]

§ 116. **Compressometers.**—Most instruments used for tensile experiments can also be used as compressometers provided that the test-piece is of sufficient length to take them. It is, however, often necessary to modify the method of attachment. The conditions applicable to the use of extensometers (§ 105) apply, with just as much force, to compressometers.

(i) The Yale extensometer (§ 107), using double micrometer screws, and the Wisconsin (§ 111) dial extensometer are both used in the U.S.A. for compression tests by a suitable modification of the clamps.

(ii) Ewing's compressometer for short blocks (Fig. 131) is on the same principle as that used for tension tests. The mechanical multiplication is, however, increased to five times, enabling readings of $\frac{1}{125000}$ of an inch to be obtained.

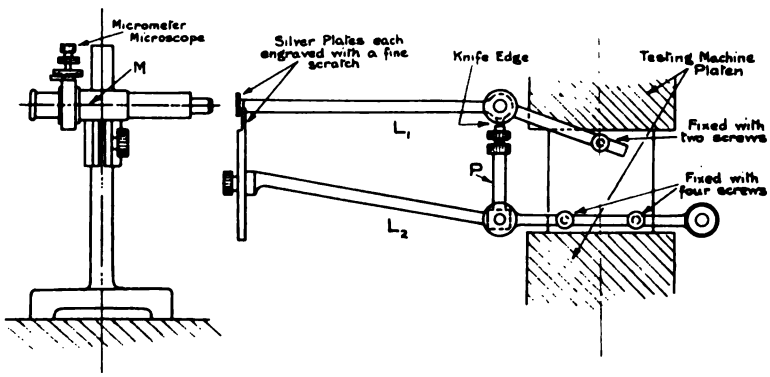

FIG. 132.—Unwin's compressometer for short blocks.

(iii) Martens' mirror arrangement (§ 115) has been used by the authors as a compressometer on diameters up to 4½ inches by providing additional springs (S, Fig. 123) to hold the clips on to the larger size of test-piece.

(iv) Unwin[24] has designed an instrument for short blocks combining lever and microscope. This instrument is shown diagrammatically in Fig. 132. The lever (L_1) being provided with a knife edge resting on the pillar (P) gives a mechanical magnification of 2½. The frame (L_2) is fixed to the specimen by four screws, and both frame (L_2) and lever (L_1) carry silver plates on their extremities, each plate being scratched with a fine line. The distance between these lines is measured by the micrometer microscope (M). Alterations of this distance with load give the

compressive strain as the mean of that on the two sides of the block.

§ 117. **Strain Gauges.**—A strain gauge is a special form of extensometer used to measure changes in length on the surface of various portions of a structure or test-bar. Whereas the object of an extensometer is to measure changes in length of the axis of a bar in order to determine the properties of materials, a strain gauge is used to find the actual distribution of the deformations at the extreme fibres of a member. The usefulness of

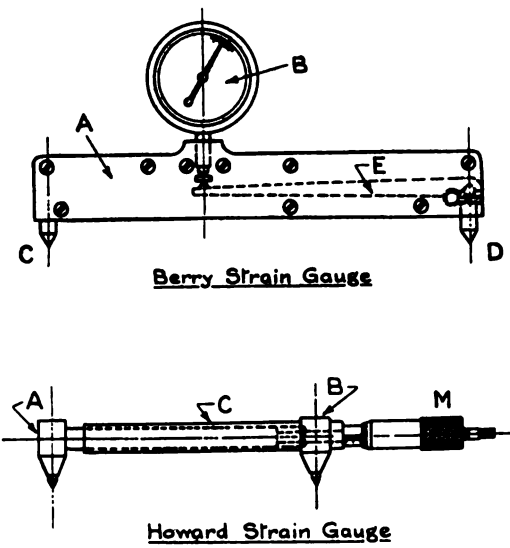

FIG. 133.—Strain gauges.

an extensometer is confined almost entirely to the laboratory, the strain gauge is the principal instrument used in "field tests" but can be employed with advantage for laboratory work.

Capps' multiplying dividers or Roberts' yield point indicator (§ 62) are types of strain gauge used for laboratory testing of materials.

Two well-known strain gauges, which are in use in the United States of America, are shown diagrammatically in Fig. 133.

(i) *Howard's Strain Gauge.*—This instrument consists essentially of a pair of trammels (A and B) mounted on a telescoping frame (C) to which is attached a screw micrometer (M) for accurately determining the movement of the points.

(ii) *Berry Strain Gauge* consists of an invar steel frame (A) to which an Ames dial (B) and two pointed legs (C and D) are attached. One leg (C) is fixed in position while the other (D) is pivoted to the frame in such a way that it adjusts itself to changes between the gauge points. Rod E is continuous with the pivoted leg and forms a bell crank lever with it. The end of this lever operates an Ames dial.

In order to secure accurate measurements it is essential that the gauge holes should be carefully made and, by using great care, readings accurate to 0·0002 inch can be obtained. Berry finds that a carefully made laying-off punch is quite satisfactory for making the gauge marks.

The instrument for commercial work is constructed for gauge lengths of 2 or 8 inches—a special research instrument for use on reinforced concrete or steel structures is made for any length from 7 to 20 inches.

§ 118. **Torsional Strain Indicators.**—For measuring elastic deformations in torsion, in order to determine the coefficient of rigidity, accurate observations are necessary. All instruments for this purpose should be independently fixed on the bar with a definite gauge length.

Where a high degree of accuracy is not essential, a convenient and simple method is to clamp two long pointers on to the specimen at a given distance apart and observe their movement over a fixed scale. The difference between the readings is a measure of the torsional strain.

(i) **Porter's Torsion Indicator.**[25]—In this indicator the long pointers of the above instrument are replaced by two rings clamped to the test-piece, at a gauge length of 3 inches, by three set screws. One clamped ring is graduated in degrees and carries on it a concentric ring engraved with a Vernier reading to five seconds of angle. The Vernier ring is supported on ball-bearings and is operated by an arm fixed to the second clamped ring. Provision is made for setting the Vernier and for any change of length of the specimen during test.

(ii) **Coker's Torquemeter.**[26]—The torsional strain is measured by this indicator on a length of eight inches. At one end of the specimen a graduated circular plate is attached to the gauge mark by three set screws. This plate carries an arm and Vernier which can be moved round it and to which is attached a frame carrying a cross wire and a mirror. At the other gauge mark a chuck, also fixed by three set screws, supports an arm having a micrometer microscope attached to it. This microscope sights on to the cross wire of the Vernier plate frame.

When the torque is applied to the test-piece the cross wire moves relatively to the microscope, and the amount of this movement is measured by the micrometer eye-piece to about one second of arc. When the strain has exceeded the range of the eye-piece the cross wire can be readjusted to zero by moving the cross-wire arm round the circular plate by means of a tangent screw.

(iii) **Unwin's Torsion Micrometer.**[27]—This instrument acts on the same principle as that designed by Coker. There are, however, one or two slight differences in detail. With Unwin's method the microscope, attached to a projection from one clip, sights on to a finely divided scale on the other clip at a gauge length of 5 inches. The micrometer eye-piece reads to 0·005 degrees.

(iv) **N.P.L. Mirror Torquemeter.**—The method usually employed at the N.P.L.[28] is shown in Fig. 134 and consists of

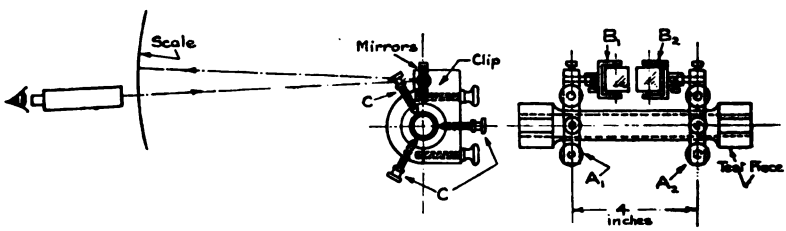

FIG. 134.—N.P.L. mirror torquemeter.

two small clips (A_1 and A_2) each fastened to the test-piece by three pointed set screws (C). Attached to these clips are the adjustable mirrors (B_1 and B_2) of a Martens mirror extensometer. The mirrors are arranged, on a gauge length of 4 inches, so that they are in the vertical plane passing through the axis of the test-piece. The method of measuring the movement of the two mirrors by the use of a single telescope has already been described (§ 115 (*c*)). The difference between the readings from each mirror at small increments of the torque give, when multiplied by a constant depending on the scale distance, the angle of twist for that increment on a length of 4 inches.

(v) **Lamb's Mirror Torsion Strain Meter.**[29]—This instrument is similar in principle to the National Physical Laboratory instrument just described, the arrangement of holders is, however, slightly different. Details of the instrument are given in Fig. 135, while Fig. 136 shows the torsion meter fitted to a test-piece. The body consists of a brass tube (B) which slides freely

FIG. 136.—Lamb's torsion strain meter.

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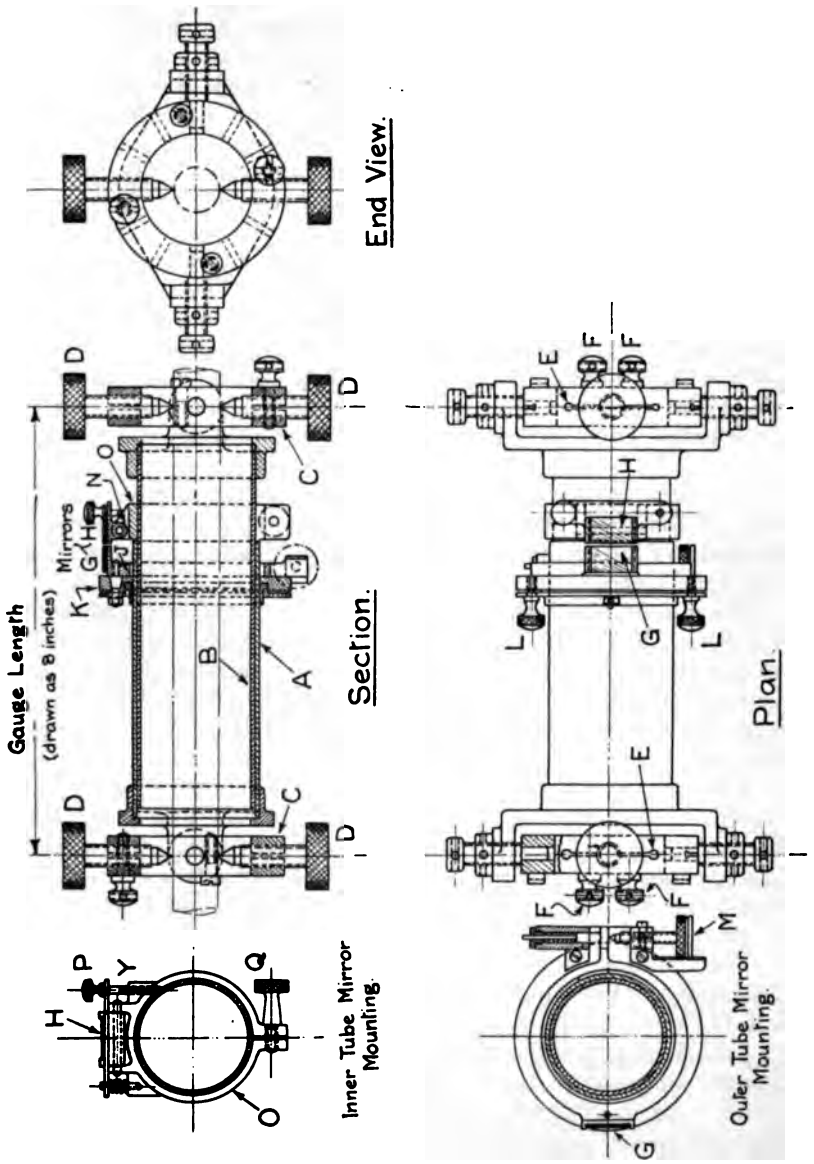

FIG. 135.—Lamb's torsion strain meter.

in another brass tube (A). Each of these tubes carries a gimbal ring (CC) at its outer end. These rings are permanently adjusted on a transverse axis and each contains two steel screws with hardened points (DD), by means of which the apparatus is attached to the specimen at the gauge points, which have previously been marked off by a suitable jig.

Each ring is slit as shown at E and this enables the gauge screws to be locked in position by means of clamping screws (FF).

The body of the instrument, as constructed, can thus be fixed to the test-piece without applying any bending strains. It applies no appreciable constraint and can therefore be used for experiments in combined bending and twisting.

Care should be taken in using the instrument to see that the axis of the specimen and of the instrument are approximately coincident. This can be regulated by adjusting the gauge screws.

The twist of the test-bar is measured by the relative movement of the two plane mirrors (G and H), one of which is attached to each of the body tubes with its plane parallel to the axis of the instrument.

The mirror (G) on the outer tube is fixed to a lever (J) pivoted on a collar (K). The collar is fixed near the end of the tube, and can swivel round the axis of the tube and be clamped in any position about that axis by screws (LL). The lever (J) can be moved about an axis parallel to that of the instrument by means of a tangent screw and micrometer head (M).

The mirror (H) on the inner tube is fixed to a lever (N) pivoted to a collar (O) about an axis at right angles to the tube axis. It is adjusted by a screw (P) to control the lateral distance between the two scale images. Collar O can be moved horizontally, as well as about the axis, and is clamped by a screw (Q) close to the mirror on the outer tube.

The relative angular movement of the two mirrors is measured by observing the relative movement of the images from the two mirrors of a scale when viewed through a telescope.

Prof. Lamb has shown mathematically that any errors due to faulty centring or flexure of the test-piece which are liable to be met with in practice are entirely negligible, and also that the "tangent error" due to using a straight instead of a curved scale can be neglected if the mirrors are suitably adjusted.

As designed the apparatus will take bars from $\frac{3}{8}$ inch up to $1\frac{1}{2}$ inches in diameter and from 8 inches to 11 inches long be-

tween the gauge points. It is being manufactured commercially by A. Macklow-Smith, 15 and 16 Queen Anne's Chambers, London, S.W. 1.

§ 119. **Deflectometers.**—These instruments are used to measure the amount of bending of beams, etc., during a transverse test.

Commercially a multiplying lever deflectometer (Fig. 109, § 91) is generally employed, or a strained wire arrangement may be used where large deflections are to be measured. This is shown in Fig. 137. A fine wire (W) is strained between two pins fixed on the neutral axis of the beam above the supports and kept taut by a rubber band (R). This forms a datum line. A polished scale (S) is graduated either in mm. or inches and suspended from the neutral axis at the centre of the beam. The

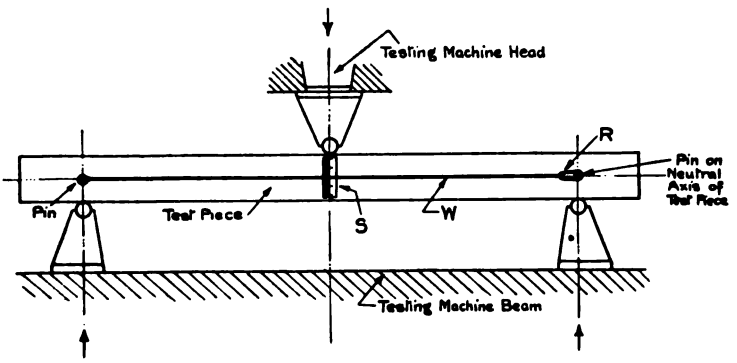

FIG. 137.—A strained wire deflectometer.

observer brings his eye to such a position that the wire and its image in the polished scale coincide and he then reads the position of the wire on the scale.

For most work an accuracy of 0·001 inch is usually sufficient.

The methods described above do not fulfil the essential conditions for accuracy, which are:—

(1) The apparatus should be designed to give the relative deflection of points in the neutral axis of the beam. This requirement is not fulfilled by the lever deflectometer.

(2) The mean deflection should be obtained. The apparatus should either provide for taking readings on both sides of the test-piece or automatically give the mean deflection. This condition is not accomplished by the strained wire arrangement.

§ 120. **Deflectometer for Timber.**—An instrument suitable for timber is shown in Fig. 81 (page 89) attached to a test-piece under four-point loading. It consists of a frame straddling the test-piece and fixed to it, on its neutral axis, by four pointed screws. The relative deflection between these points and the centre of the beam is measured by fixing a little stirrup at the centre of the span, also on the neutral axis, by two pointed screws, one on either side of the beam. When the beam deflects the stirrup pulls on a lever by means of a flexible strip of metal. The lever is pivoted on the frame and works a rack and pinion which rotates a pointer round a graduated dial.

The instrument is shown with two dials worked by arms of different leverages. That on the left gives deflections up to 0·5 inch, by 0·001 inch divisions, and is suitable for determinations of the modulus of elasticity and limit of proportionality, while the indicator on the right reads up to 2 inches, by 0·01 inch

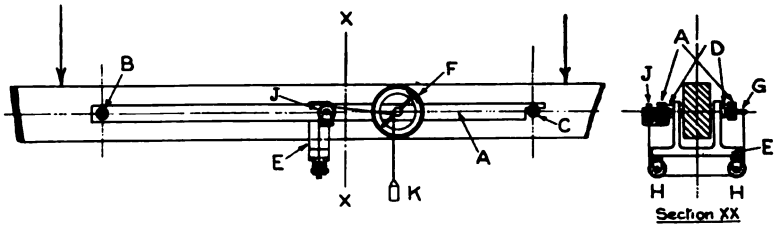

Fig. 138.—Wire-wound dial deflectometer.

divisions, and is used for continuing the deflection readings up to the breaking point of the beam. For this purpose it is provided with a maximum deflection hand on the dial. This type of deflectometer is made by W. &. T. Avery, Ltd.

Wire-wound Dial Deflectometer.—An instrument in use at the University of Wisconsin has been found to give satisfactory results for measuring small deflections. It is shown diagrammatically in Fig. 138. The datum bars (AA) are pivoted on pins (BB) and freely supported on pins (CC) let into the sides of the beam at the neutral axis. Washers (DD) are provided to keep the datum bars at a fixed distance from the sides of the specimen to enable the yoke (E) to be attached at the centre of the span by means of thumb screws. The motion of the yoke relative to the datum pins (BB and CC) is indicated on a dial (F) and is obtained by means of an arrangement of pulleys and wire. One end of a thin flexible wire is attached to a pin (G) fixed to the centre of one datum bar. The wire is carried

over pulleys HH, attached to the yoke, and pulley J fixed to the other datum bar and is then wrapped round the pointer axle of the dial (F). A weight (K) keeps the wire taut and thus enables twice the relative deflection to be indicated on the dial.

§ 121. **Apparatus for Measuring Lateral Strains.** — (i) **Coker's Lateral Strain Measuring Apparatus.**[30] — This instrument is shown diagrammatically in Fig. 139 and consists of two tubular arms (A_1 and A_2) connected by a flexible steel plate (B) which forms the fulcrum. The steel plate is gripped by two collars (CC), one of which carries an adjustable screw (L) which bears on the test-piece and keeps the instrument from turning. The arms are attached to the test-piece (T) by two screws (DD), the pressure on which is provided by the com-

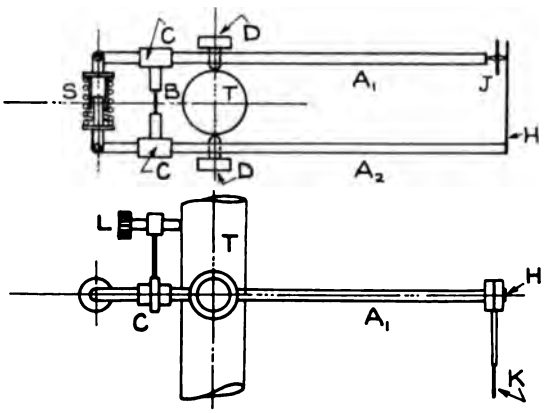

FIG. 139.—Coker's lateral strain measuring apparatus.

pression of a spiral spring (S) on the opposite side of the fulcrum.

The arm A_2 has a projection H, the end of which is opposite to the arm A_1 and is arranged to spring towards it gripping a knife edge J.

Any change in the diameter of the test-piece causes a relative movement between the end of the arm A_1 and the projection (H) of the arm A_2. This movement rotates the knife edge (J) to which a mirror (K) is attached. The rotation of this mirror is observed by a telescope and scale and gives a measure of the alteration in the diameter of the test-piece. The scale distance is arranged so that each scale division represents 0·000001 inch.

(ii) **Morrow's Instrument for Measuring the Lateral Contraction of Tie Bars.**—This instrument,[31] shown diagrammatically

in Fig. 140, also uses optical means of measuring the relative displacement of two arms.

Two arms (KK and LL) are pivoted at F and two screws (A and B) grip the test-piece (T) and are pressed inwards by a stiff spring (C). Alteration in the diameter of the test-piece causes the arm K to fall relatively to the arm L. This relative motion is measured by the tilt of a mirror (M) which is supported on three points, two of which rest on arm L and one on arm K. A vertical mirror, not shown, is also fixed to L at the side of the tilting mirror (M) and the image of the scale in this mirror serves as an index for reading the rotation of the tilting mirror (M) thus eliminating any errors due to the instrument moving relatively to the observing telescope. The instrument is balanced by a weight (W).

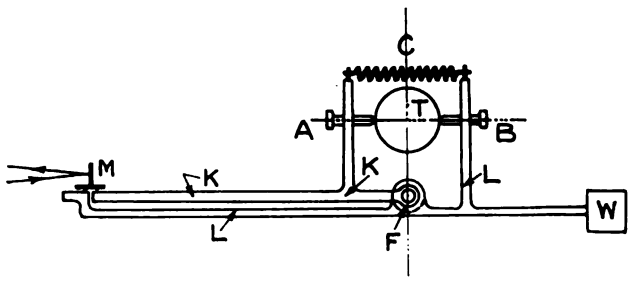

FIG. 140.—Morrow's instrument for measuring lateral contraction.

A somewhat similar instrument is used by Cook and Robertson [32] for determining the diametral extension of cylinders.

§ 122. **Calibration of Deformation Measuring Apparatus.**—The usual methods of obtaining the constants of extensometers, compressometers, etc., are:—

(1) By measurement of the leverage of the instrument. In some types of apparatus this can be carried out successfully. With the Martens mirror extensometer the constant depends on the width of the rhombs and the scale distance. The former can be determined by an accurate measuring machine and the latter is usually adjusted by setting the scale distance from the test-piece by means of a gauge of known length.

(2) By test on a steel test-piece whose elastic constants have been accurately determined. The test-piece is gripped in the testing maching in such a way that the stress is distributed in the proper manner and readings of the apparatus which is to

be calibrated, taken at definite increments of the load. These readings are then compared with those calculated from the known elastic constants. If possible a standardised apparatus is attached to the test-piece at the same time as the one whose constants are unknown and a direct comparison made.

(3) By a calibrating instrument. An instrument used by the authors is shown in Fig. 141 and consists of a stand (D) carrying two arms (E_1 and E_2). These arms are movable along a feather on the stand so that their position can be adjusted. They are bored accurately in line to take two rods (A and B). B is fixed, but A can be moved up and down by a micrometer head (C). A also works along a feather which prevents rotation.

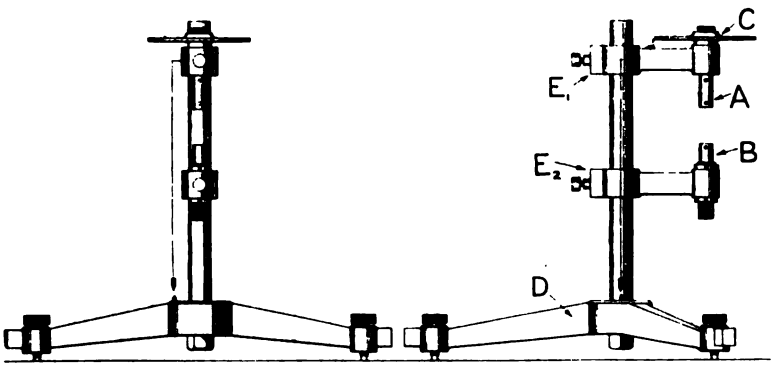

FIG. 141.—Apparatus for calibrating extensometers.

The apparatus to be calibrated is attached to A and B and its readings compared with the movement of the micrometer head. The pitch of the micrometer screw is 0·025 inch, and the head is divided into 25 parts so that one division (about ½ inch long) of the head corresponds to a movement of 0·001 inch.

It is essential that the desired reading should always be approached in the same direction in order to eliminate any backlash in the screw. As the accuracy of the calibration depends upon the accuracy of the screw this has been determined on a screw-measuring machine and a correction curve obtained for it. An instrument similar in principle but slightly different in construction has recently been described by Templin.[33]

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CHAPTER XII.

AUTOGRAPHIC RECORDING APPARATUS.

§ 123. THE deformation co-ordinate of the curve is always recorded directly from the test-piece itself usually with some form of multiplication. The main difference in the various types of recorder is in the method of obtaining the load co-ordinate. There are two principal ways in which this is done :—

(1) Load recorded by the movement of the counterpoise with or without automatic adjustment.

(2) Load co-ordinate obtained by the deformation of a calibrated spring.

§ 124. The early diagramming apparatuses were applied to pendulum machines. Thurston, in 1876, designed the torsion test apparatus described in § 42 (iii), page 71, and, in 1877, Abbott constructed a recorder adapted to a machine in which the pull from an hydraulic press is transmitted through the test-piece to a pendulum, the angular rise of which gives a measure of the load. An improved apparatus of the same kind was used by Pohlmeyer in 1882 and more recently by the N.P.L. for tests of copper and bronze wires fully described in the British Engineering Standards Association Report, No. 55.

In machines having a moving counterpoise the load co-ordinate is obtained from the position of the counterpoise on the beam by moving a drum or pencil, by suitable pulleys or gearing, from the shaft or screw which drives the counterpoise. The beam is usually kept floating by moving the poise by hand adjustment. By this means, however, the reduction of load at the yield point cannot be obtained and the final reduction, when the test-piece is stretching locally, is only imperfectly reproduced.

§ 125. **Riehlé Autographic and Automatic Apparatus.**— In some American machines an autographic apparatus is provided having an automatic weighing device. This device is designed to move the poise on the beam automatically to balance the load on the specimen. In the Riehlé machine the scale beam on

rising or falling completes an electric circuit at the top or bottom stop in the beam stand. Each circuit is separate and connected to a magnet.

The driving pulley of the machine turns a horizontal shaft which has a cast-iron disc on its end (see Fig. 142). This disc in turn drives one of two fibre wheels located equidistant on either side of the centre of the disc. Each fibre wheel has an armature controlled by one of the magnets of the electric circuits mentioned above. Thus when the beam (A) rises and completes the top circuit, one of the magnets attracts its armature causing one of the fibre wheels to engage with the cast-iron disc and drive the poise along the beam and so balance the load. When the beam drops and hits the lower contact, the armature of the other fibre wheel is attracted by its magnet which brings this fibre wheel on to the cast-iron disc and drives the poise in the opposite direction.

The screw which drives the poise also, through gearing, drives the recording pencil axially along the drum (G) so that the reading of the load which is recorded corresponds directly to the load weighed.

The other ordinate is obtained by the drum revolving proportionally to the deformation. "Fingers" rest on top of U clamps fastened to the specimen by hardened steel-pointed set screws at the correct gauge distance. The lower "finger" moves downwards as the test-piece extends and by means of a rack and pinion converts this motion into a rotary one revolving the drum through mitre wheels. The actual extension is magnified five times. The fingers are so arranged with clamps on telescopic tubing that only the extension between the U clamps is recorded on the diagram.

§ 126. **Load Co-ordinate Obtained by the Deformation of a Calibrated Spring.**—This method is used in two Wicksteed recorders. In the earlier apparatus[1] (Fig. 143) the measurement of the stress is entirely independent of the position of the poise on the beam but is taken as being proportional to the compression of a helical spring (C) acted upon by an auxiliary plunger (R) operated by hydraulic pressure from the straining cylinder of the testing machine. As the load is applied by the straining cylinder it is balanced by running the poise along the beam, and the hydraulic pressure in both the straining cylinder and the auxiliary cylinder increase. The auxiliary plunger therefore compresses the spring and the amount of the movement of the spring is recorded by a pencil (P) on the recording paper in a

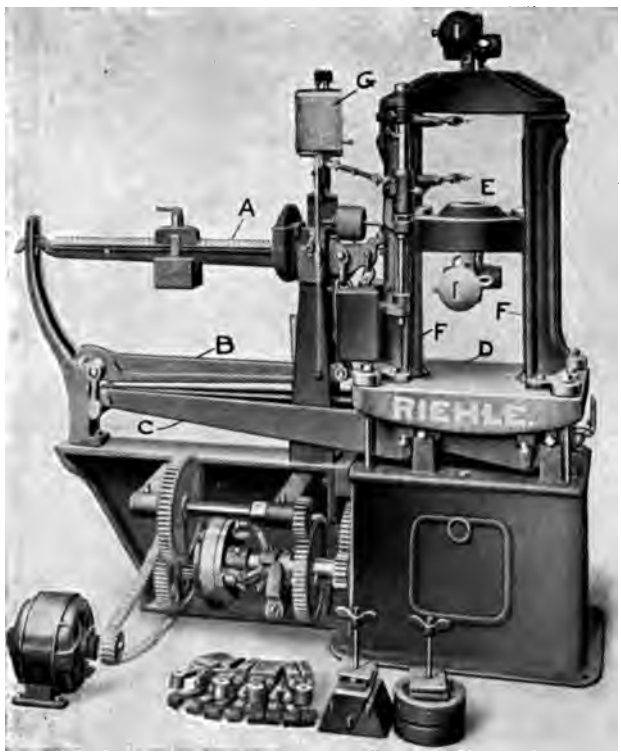

FIG. 142.—Riehlé testing machine.

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direction parallel to the axis of the drum (D). The drum is also

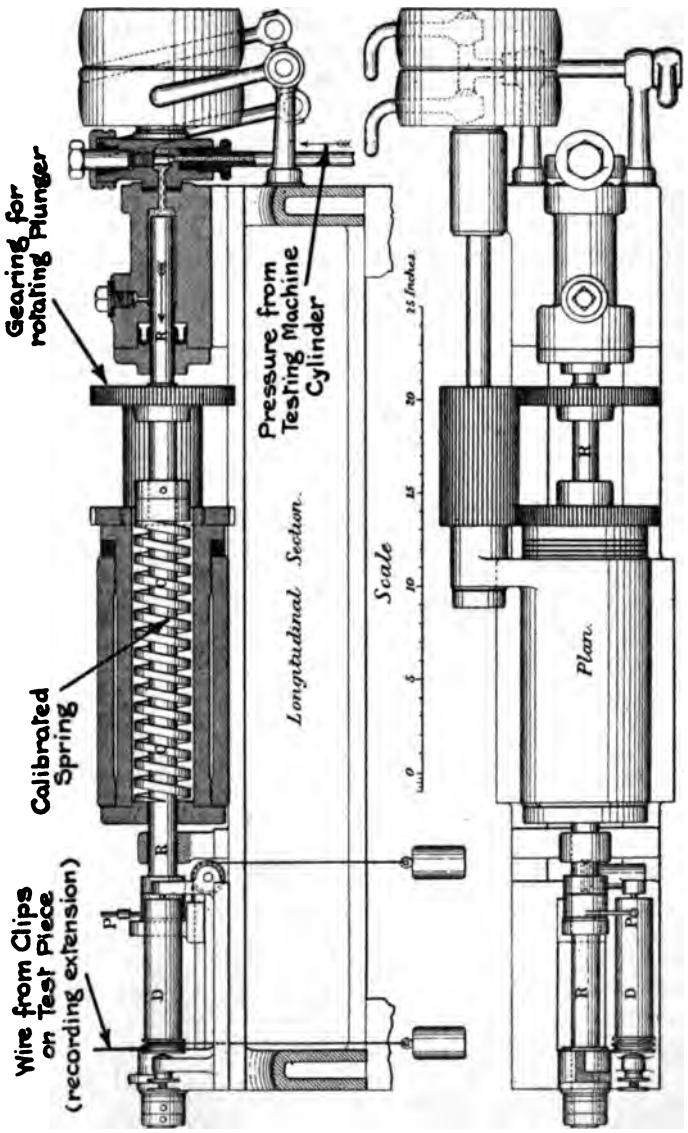

FIG. 143.—Wicksteed's autographic load-extension recorder.

given a rotation proportional to the extension of the test-piece and an automatic diagram is thus drawn.

The auxiliary plunger is rotated, by the gearing shown, during the test in order to eliminate the friction as far as possible. The yield and maximum loads are noted from the position of the counterpoise in order to fix the load scale of the diagram.

§ 127. **The Buckton-Wicksteed Patent Spring Balanced Recorder** is entirely automatic and the variations in the resistance of the specimen are accurately recorded. The action of the recorder is shown diagrammatically in Fig. 144. The counterpoise (P) is placed at the end of its travel thus extending the spring (S). As the load (W) is applied to the test-piece an equivalent load is released from the spring (S) which therefore contracts. The amount of this reduction in length is proportional

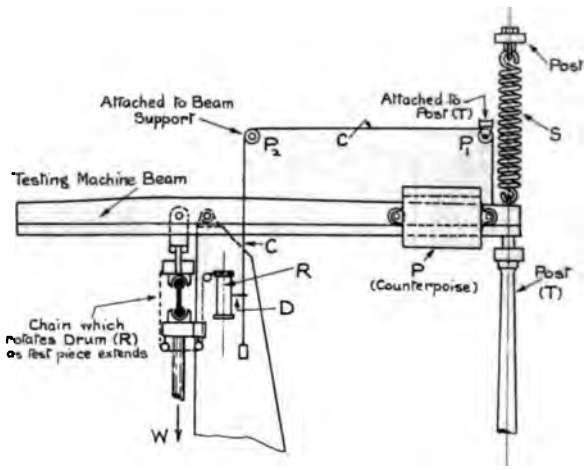

FIG. 144.—Diagram of the Buckton-Wicksteed patent spring balanced recorder.

to the load on the test-piece and is registered on the recording drum (R) by means of a cord (C) passing over fixed pulleys (P_1 and P_2) and attached to the pencil (D) of the apparatus.

The load is thus recorded axially and the drum is rotated, by the movement of the lower pulling head relatively to that of the upper shackle, to give the deformation co-ordinate As the deformation is not communicated from a fixed gauge length of the test-piece, it includes movement in the grips and cannot be taken as the extension of the specimen.

§ 128. **Moore's Autographic Recorder**[2] is very similar in action to the Wicksteed spring recorder just described, the only difference being that the spring is placed on the other side of the

principal knife edge so that when the poise is run out the spring is compressed. As the load is applied to the specimen an equivalent load is released from the spring which elongates until equilibrium is established. Moore used a steam engine indicator; the spring of the indicator is attached to the beam of the testing machine to give the load co-ordinate, and the cord of the indicator is attached to the test-piece to record the extension.

§ 129. **Kennedy-Ashcroft Recorder**[3] (Fig. 145).—Full details of the recorder are given in Kennedy's paper to the Institution of Civil Engineers and the following description of the principle of the apparatus is also taken from that paper:—

"The test-piece *a* is placed in the machine in SERIES with a stronger bar B, called a spring-piece, and the two, which are connected directly by a simple coupling, are pulled simultaneously, the one through the other. The spring-piece is of a material such that its limit of elasticity occurs only at a load greater than that which will break the test-piece. It must also be of material

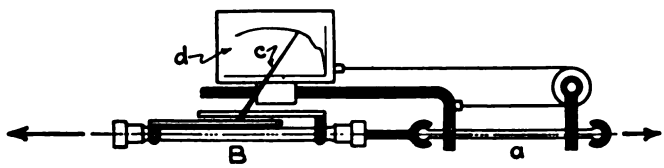

FIG. 145.—Kennedy-Ashcroft recorder.

ascertained by previous experiment to be perfectly elastic, so that its extension is strictly proportional to the pull on it, and therefore to the pull on the test-bar. By a simple arrangement a very light pointer *c* is made to swing about an axis through an angle proportionate to the extension of the spring-piece, and proportional, therefore, to the pull on the test-bar. The end of this pointer in its motion always touches a sheet of smoked glass *d*, to which is given a travel—in its own plane—proportional to the extension of the test-piece, and in this way the diagram is drawn. By an arrangement of differential levers it is assured that the motion of the glass depends solely on the extension between the marked points on the test-bar, so that no amount of extension of the coupling, in the ends of the test-piece, or in any other part of the apparatus, can move the glass. The apparatus is also so arranged that the absolute elongation of the spring-piece does not cause any motion of the pointer relatively to the glass."

§ 130. **Dalby's Optical Recorder.**[4]—This apparatus is similar to the Kennedy-Ashcroft recorder in that the load is

obtained from the extensions of a bar acting as a very stiff spring but, whereas Kennedy used mechanical means of increasing and transferring these extensions to the diagram, Dalby adopts an

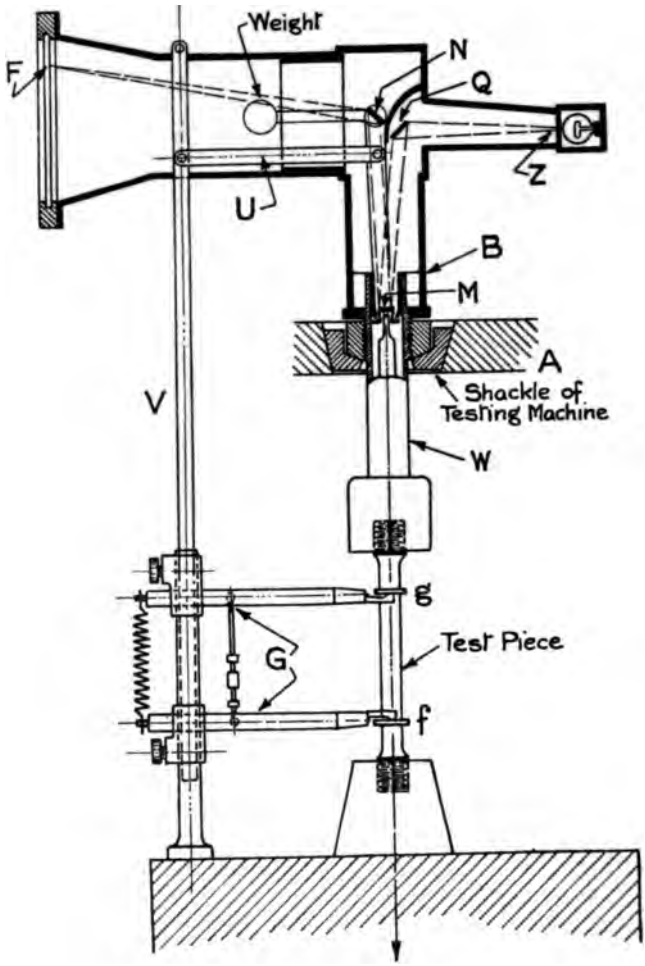

FIG. 146.—Dalby's optical recorder.

optical photographic method and thus obviates the possibility of inertia errors.

Fig. 146 indicates the principle employed in the apparatus and Fig. 147 shows the method of transferring the elastic exten-

sion of the spring-piece to a rotation of a mirror. The spring-piece (W) is hollow and is connected at its upper end to the shackle (A) of the testing machine. A projection through the shackle is mounted in a light tight box (B). The ray from a point of light (Z) is reflected by a fixed mirror (Q) on to a concave mirror (M) which again reflects it on a third mirror (N) and

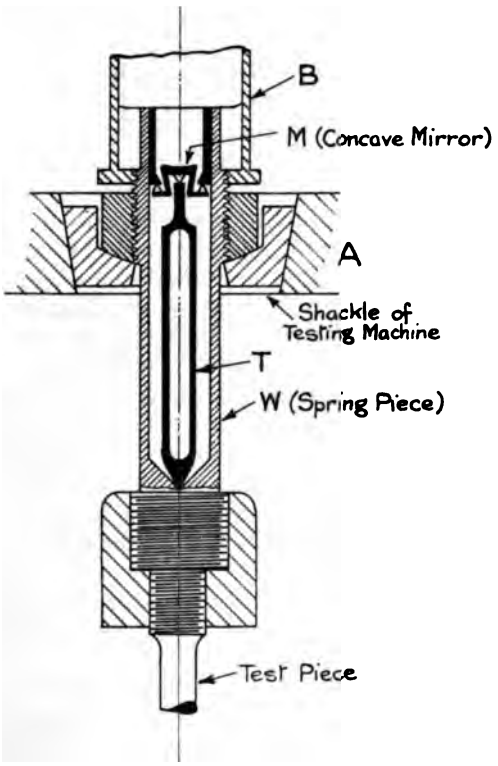

FIG. 147.—Dalby's optical recorder (the spring piece).

thence to a photographic plate at F where it is accurately focussed.

The mirror (M) is supported on three points, two of these about which the mirror can tilt are in contact with the hollow spring bar while the third rests on a cup on the top of the central rod (T). Any stretch of the spring bar (W) will cause it to move relatively to the central rod (T) and thus tilt the mirror (M). This tilt will cause the point (F) to move horizontally

across the photographic plate a distance of 340 times the stretch of the bar.

The mirror (N) is rotated by the linkwork G proportionally to the stretch of the test-piece between the gauge length *gf*, and this movement displaces the point (F) vertically up and down on the photographic plate. The point of light therefore traces on the plate a load-extension diagram of the test made. After development the relation between load and extension can be measured from the plate.

In the latest design, the mirror arrangement of the weigh bar is placed at the lower end of the latter. This enables the complete instrument to be attached to or removed from the testing machine without interference with the connection between the weigh bar and the mirror box and at the same time simplifies the special attachments required for any type of testing machine. It will be noticed that the test-piece is turned with collars *g* and *f* spaced a convenient distance apart and the extension between these collars is measured by suitable mechanism bearing lightly against the collars. Prof. Coker [5] has made an optical investigation of the distribution of the stresses in this form of test-piece and states that "the experiments appear to show that although flanges cause a local increase of stress, the form of the curve, by which they merge into the main body of the member is not very important provided it does not undercut the specimen". He further states that "the evidence appears to justify the use of this form of test-piece for tension tests, although there is a local increase of stress at or near the join of the straight contour with the flanges. The local concentration with this form is also met with in the usual standard forms under less advantageous circumstances."

The necessity for the very careful turning at the collars renders this test-piece much more expensive to machine and this increased cost will probably prohibit its use for commercial work.

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CHAPTER XIII.

DETERMINATION OF THE ELASTIC CONSTANTS.

§ 131. AN account of load-extension or stress-strain diagrams is given in Chapter III (§ 25-29). The complete diagram is drawn by means of some form of autographic diagram apparatus (see Chapter XII), but for the accurate determination of the elastic limit and modulus of elasticity it is necessary to determine with extreme accuracy the deformations produced by small loads.

§ 132. **The Elastic Limit.**—The elastic limits in tension and compression obtained from stress-strain curves on the first loading of a piece of material such as steel are not constant for the material but depend upon the previous treatment that the material has undergone. They are called the "primitive" elastic limits to distinguish them from the "natural" elastic limits set up in the material when it is subjected to a few alterations of stress.

The definition of the elastic limit which has been standardised by the British Engineering Standards Association and is commonly accepted in this country is that it is the least stress at which Hooke's Law ceases to be exact. It is sometimes called the limit of proportionality or the " P " limit.

Owing to the fact that with some materials there is a deviation from proportionality between stress and strain even at small values of the stress (although the material regains its original dimensions when the stress is released), another definition is sometimes used. It is occasionally taken as the maximum stress below which the material would fully recover its form upon removal of the load. This may be called the " R " limit. With most materials the two definitions give substantially the same results, they both require delicate extensometers for their determination but the method of procedure during the test is slightly different.

In the first case extensometer readings are taken with gradually increasing loads and the results plotted as a load

extension diagram. The point at which there is a deviation from Hooke's Law is easily located and the modulus of elasticity can be calculated from the slope of the elastic line. The increments of load taken are usually about $\frac{1}{15}$ of the estimated value of the "P" limit, and if the value of the "P" limit is known to a first approximation the increments are made smaller in the neighbourhood of that value and until the test is completed.

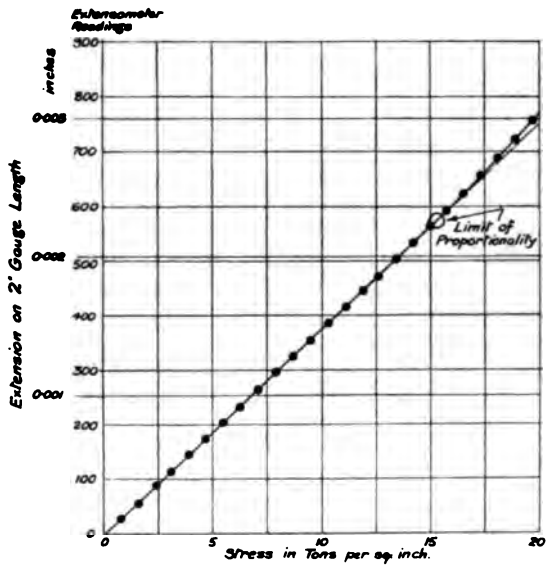

FIG. 148.

The following measurements (Table XXXVIII) are taken from a specimen machined from a piece of steel and show how a the "P" limit and the modulus of elasticity can be calculated.

The results are plotted in Fig. 148 and show that the limit of proportionality is at 15·3 tons per square inch. From the elastic line it is seen that where the extension on 2 inches is 0·002 inch (i.e. a strain of 0·001) the intensity of stress is 13·55 tons per square inch.

TABLE XXXVIII.

RESULTS OF AN EXTENSOMETER TEST ON STEEL.

Diameter of test-piece = 0·564 inch.
Cross-sectional area = 0·2498 sq. in.
Extensions measured on a 2-inch gauge length by a mirror extensometer.

Stress in Tons per Sq. In.	Extension Readings * on a 2-in. Gauge Length.	Calculated Elastic Extension.*	Permanent Set.*
0·00	0	0	0
0·79	30	30	0
1·58	57	59	− 2
2·36	88	89	− 1
3·15	115	118	− 3
3·94	146	148	− 2
4·73	176	178	− 2
5·52	207	207	0
6·31	234	237	− 3
7·09	265	266	− 1
7·88	295	296	− 1
8·67	324	326	− 2
9·46	355	355	0
10·24	384	385	− 1
11·04	414	414	0
11·82	444	444	0
12·61	473	474	− 1
13·40	504	503	+ 1
14·19	533	533	0
14·98	563	562	+ 1
15·76	593	592	+ 1
16·55	625	622	+ 3
17·34	656	651	+ 5
18·13	690	681	+ 9
18·92	722	710	+ 12
19·70	757	740	+ 17
20·49	793	770	+ 23
21·28	830	799	+ 31
22·07	874	828	+ 46
22·86	914	858	+ 56
23·65	981	887	+ 94
24·43	1054 *	917	+ 137

Results of test:—

Limit of proportionality	= 14·2 tons per sq. in.
Yield stress	= 24·4 ,, ,, ,,
Ultimate stress	= 45·8 ,, ,, ,,
Modulus of elasticity	= 30·3 × 10^6 lbs. per sq. in.
Extension on 2 ins.	= 21·0 per cent.
Reduction of area	= 32·9 ,, ,,

* 1 unit = 1/254,000 ins., i.e. 1054 units = 0·0415 in.

Therefore the modulus of elasticity (E) $= \frac{\text{stress}}{\text{strain}} = \frac{13{\cdot}55}{0{\cdot}001}$

$= 13{,}550$ tons per square inch.

$= 30{\cdot}3 \times 10^6$ lbs. per square inch.

The formula for calculating the modulus of direct elasticity is devised thus :—

If A = cross sectional of the test-bar in square inches
L = gauge length in inches
P = load in tons
x = extension in inches at a load of P tons.

$$E \text{ (modulus of elasticity)} = \frac{\text{stress}}{\text{strain}} = \frac{P}{A} \div \frac{x}{L}$$

$$= \frac{PL}{Ax} \text{ tons per square inch}$$

$$= 2240\frac{PL}{Ax} \text{ lbs. per square inch.}$$

Substituting the figures from the above example we have

$$E = \frac{2240 \times 13{\cdot}55 \times 2}{0{\cdot}002} \left(\text{Note, } \frac{P}{A} = 13{\cdot}55\right)$$

$= 30{\cdot}3 \times 10^6$ lbs. per square inch.

If the readings of the extension and the applied load are known to sufficient accuracy the limit of proportionality can be ascertained with more precision by calculating the elastic extension for the various loads applied and plotting the difference between this and the actual extension as ordinates with the loads as abscissæ. Table XXXVIII shows this calculation and the results are plotted in Fig. 149.

It will be noted that, whereas the curve in Fig. 148 shows the limit of proportionality to be about 15·3 tons per square inch, the method of reducing the results plotted in Fig. 149 indicates that it is probably nearer 14·2 tons per square inch. It is obvious therefore that the value obtained for the limit of proportionality depends to a large extent upon the sensitiveness of the extensometer and the method of deducing the result.

Prof. Bairstow during some experiments on the elastic recovery of steel found that, when he used the standard Martens extensometer in which one scale division was equal to $\frac{1}{254000}$ inches, he obtained an apparently higher limit of proportionality of the steel after treatment. He therefore constructed and used

a mirror extensometer of four times the sensitiveness when he discovered that the limit of proportionality actually remained unaltered; the deviation from proportionality after treatment was so gradual that he had been unable to detect it with the standard mirror instrument.

It is of first importance that shocks and vibrations should be avoided during the application of the load in an extensometer test since actions of this kind seriously affect the sensitivity and the accuracy of the instrument.

The second method of procedure, employed to determine the (R) limit, is to apply an increment of the load and upon its

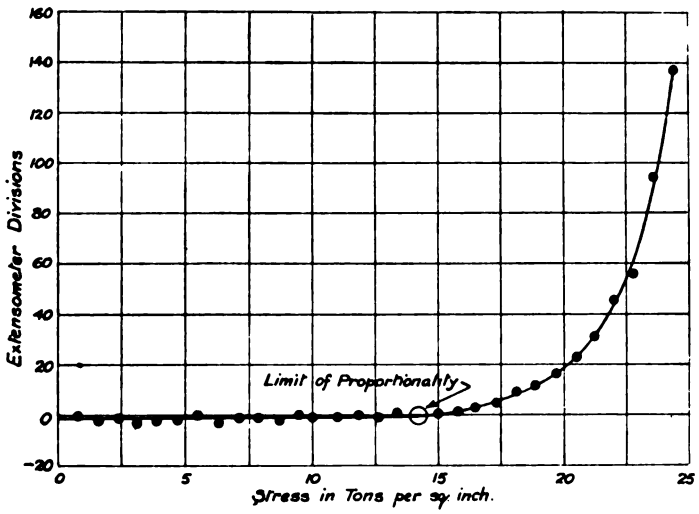

FIG. 149.

release measure the amount of the permanent set, if any. The load is then doubled and the set on release again measured. A further increase of the load is applied and released and the operation repeated until a well defined and increasing permanent set is obtained.

The amount of the permanent set is plotted against the load and an estimate obtained, from the curve, of the point at which the material starts to have a permanent set. From this reading the "R" limit is calculated.

The determination of the "R" limit requires considerable time to carry out but indicates plastic yielding of the material at an early point when it is properly ascertained.

§ 133. **Elastic Limit by Change of Temperature.**—If a material behaves elastically, increasing load produces a cooling of the test-piece but if, however, a permanent set is produced, work is done in internal friction and the temperature of the test-piece rises. E. Rasch,[1] of Gross Lichterfelde, has carried out some experiments to determine the temperature—load curve for materials. For temperature measurement he uses thermo-couples of iron-constantan, copper-constantan, or silver-constantan bound to the test-piece. Alterations of the temperature are read from the movement of a galvanometer. He finds well-defined points of inflection in his curves. The loads at which these points occur give an elastic limit sometimes called the thermal or "T" limit.

§ 134. **Effect of Overstrain on Elastic Limit and Yield Point.**—Bauschinger found the effect, on the *limit of proportionality*, of overstrain to be as follows:—

(1) If the limit of proportionality was exceeded, but not the yield point, then the *former is raised* even if the test-piece is immediately reloaded.

(2) If the yield point is exceeded, immediate reloading gives a *lower limit of proportionality* but reloading after a long interval of time may give a *raised limit of proportionality*. James Muir[2] found that this effect can be accelerated by immersion for a few minutes in boiling water.

Bauschinger also found that the *effect on the yield point* was that if the yield point was exceeded then subsequent reloading gave a *new yield point raised* to the stress to which the bar was loaded in the first place. This effect occurred even if the bar was reloaded immediately, but if there was an appreciable interval of time before the reloading the new yield point might be higher than the maximum stress applied in the first loading.

§ 135. **The Modulus of Elasticity.**—The modulus of elasticity is the number by which the amount of any specified stress or component of a stress within the limits of elasticity must be divided to find the strain or any stated component of the strain which it produces.

There is a modulus of elasticity in tension, compression and shear.

The modulus of elasticity in tension, denoted by E, is sometimes called the modulus of direct elasticity or Young's modulus. The value in compression is generally the same as that in tension.

The modulus of elasticity in shear, denoted by C, is called the modulus of transverse elasticity or the modulus of rigidity.

There is also a volumetric modulus of elasticity, sometimes called modulus of elasticity of bulk or modulus of cubic compressibility, and denoted by K. It is the number by which the stress upon the exterior of the substance must be divided to give the diminution in volume or cubical strain.

If E and C are known, K can be calculated from the formula :—

$$K = \frac{CE}{9C - 3E} \text{ or } K = \frac{E}{3(1 - 2/m)}$$

where $\frac{1}{m}$ = Poisson's Ratio (see § 7 and 140).

§ 136. **Modulus of Direct Elasticity.**—An example of the method of determining the modulus of direct elasticity (E) is given in § 132. Some materials, e.g. cast iron, mortars and concrete, have no elastic line and therefore no definite modulus of direct elasticity. It can, however, be considered to be the reciprocal of the slope of the stress-strain curve at zero stress but where the curvature near the origin is sharp this value of the modulus is of little use except as a comparative value of stiffness.

An example of a stress-strain curve with no definite elastic line is given in Fig. 150. The initial modulus of direct elasticity is obtained from the slope of the tangent (OA) to the curve at the origin.

For concrete an empirical modulus is sometimes used for design calculations. The value is obtained in one of three ways :—

(1) The "tangent" modulus (E_t) is obtained from the slope of the tangent to the stress-strain curve where the ordinate is the working stress—25 per cent. of the compressive strength is usual for the working stress—that is from the tangent CD (Fig. 150).

(2) The "secant" modulus (E_s) is obtained from the slope of the line OB where B*b* equals the working stress of the material.

(3) The "chord" modulus (E_c) determined by the ratio of stress to deformation is given by the chord drawn between two points on the curve, defined by the limits of stress for working loads, i.e. from the chord EF (Fig. 150).

The tangent and chord methods give modulii of approximately the same value, which are higher than the secant modulus.

Stanton Walker[3] has shown, from a study of curves which

he obtained from various samples, that the stress-strain curve is represented by a curve of the type $S = Kd^n$

where S = unit stress in concrete
d = unit of deformation
K = constant depending on strength
n = an approximately constant exponent

and the relation between modulus of elasticity and strength of concrete is $E = CS^m$

where E = modulus of elasticity
C = constant depending on conditions of test
S = compressive strength of concrete
m = an exponent.

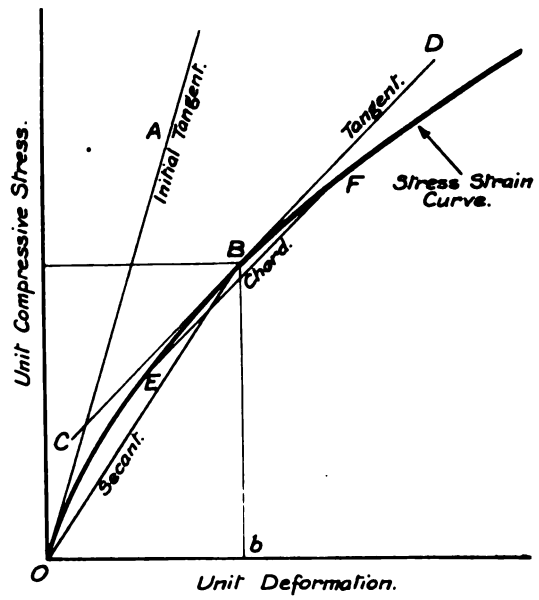

FIG. 150.—Stress-strain curve with no elastic limit.

Similar equations were suggested by Bach and Morsch.[4]

§ 137. **Effect of Overstrain on the Modulus of Direct Elasticity.**—If the limit of proportionality is exceeded the value of E for steel may be lowered, in some cases as much as 20 per cent. Recovery, however, is effected by rest or immersion in boiling water. Marshall [5] showed that if steel is initially strained to a point within the limit of proportionality a second loading may give slightly higher values of E.

§ 138. **Values of the Modulus of Direct Elasticity (Young's Modulus).**—For carbon steels the value of E in lbs. per square inch varies between $28{\cdot}5 \times 10^6$ and 31×10^6 with an average value of $29{\cdot}5 \times 10^6$.

For low percentage nickel steels (3 to 4½ per cent.) the average value of E is $28{\cdot}5 \times 10^6$ lbs. per square inch while the value of E for high percentage nickel steels (30 to 35 per cent.) is low, being about 23×10^6 lbs. per square inch.

With cast iron there is no definite modulus of elasticity. Using a working stress figure of 10,000 lbs. per sqare inch the "secant" modulus for cast iron varies from 12×10^6 to 20×10^6 lbs. per square inch for grey cast iron and from 20×10^6 to 25×10^6 lbs. per square inch for white cast iron.

In a very extensive series of tests on carbon steels, Brinell,[6] in 1901, found that heat treatment had very little effect on the value of the modulus of direct elasticity for steels having a carbon content varying from 0·09 to 1·17 per cent.

A brief account of the results of the determinations, made at the National Physical Laboratory, of the modulus from direct tension and compression tests of steels of varying heat treatment may be of interest. The determinations were in all cases made with a mirror extensometer and it is considered that the results, except in a few cases in which the limit of proportionality was very low, are accurate to ± 1 per cent.

From the results which are given in Tables XXXIX and XL it will be seen that the variation is very small. The greatest range in the value of E in the individual tensile test results is from $28{\cdot}1 \times 10^6$ lbs. per square inch for a 2¾ per cent. nickel, 0·25 per cent. carbon steel, quenched and tempered at 400° C., to $29{\cdot}9 \times 10^6$ lbs. per square inch for a 1¾ per cent. nickel, 1¼ per cent. chromium, 0·35 per cent. carbon steel, quenched and tempered at 650° C.; a difference of 6 per cent. The maximum effect due to heat treatment alone was found in the case of the 2¾ per cent. nickel, 0·25 per cent. carbon steel, and was 4 per cent. The result of the tests in compression (Table XLI) show a similar small variation.

The modulus of direct elasticity is nearly the same in tension as in compression. The results of experiments made on the same materials in tension and compression by means of axial loading shackles are given in Table XLII.

In Table XLIII particulars are given of various grades of brass and phosphor-bronze together with the values of their modulus of direct elasticity. Further values of E are given in Table XLIV.

TABLE XXXIX.

EFFECT OF HEAT TREATMENT ON THE MODULUS OF ELASTICITY IN TENSION.

Steel.		0·15 per Cent. Carbon Steel.	0·20 per Cent. Carbon Steel.	2·5 per Cent. Nickel. 0·15 per Cent. Carbon.	2½ per Cent. Nickel. 0·25 per Cent. Carbon.	3·5 per Cent. Nickel. 0·35 per Cent. Carbon.
Normalising and quenching temperature, °C.		900	900	880	860	860
MODULUS OF ELASTICITY IN LBS. PER SQ. IN.						
Normalised	—	$10^6 \times 29{\cdot}4$	—	$10^6 \times 29{\cdot}5$	$10^6 \times 28{\cdot}5$	$10^6 \times 29{\cdot}1$
Water quenched	—	29·3	—	29·6	28·9	28·4
Water quenched and tempered at	300	29·6	—	29·5	28·7	28·4
	400	29·4	—	29·6	28·1	29·2
	500	29·6	—	29·5	28·8	28·5
	600	29·4	—	29·4	28·8	29·0
	650	—	—	—	29·1	29·1
Oil quenched	—	$10^6 \times 29{\cdot}6$	$10^6 \times 29{\cdot}6$	$10^6 \times 29{\cdot}6$	$10^6 \times 29{\cdot}2$	$10^6 \times 28{\cdot}7$
Oil quenched and tempered at	300	—	—	—	28·8	29·1
	400	—	—	—	29·0	28·7
	500	—	—	—	29·1	29·0
	600	—	29·6	29·2	29·0	28·7
	650	—	—	—	28·9	29·0
Water quenched, reheated and water quenched	from 760	—	$10^6 \times 29{\cdot}6$	$10^6 \times 29{\cdot}5$	—	—
Average		$10^6 \times 29{\cdot}5$	$10^6 \times 29{\cdot}6$	$10^6 \times 29{\cdot}5$	$10^6 \times 28{\cdot}9$	$10^6 \times 28{\cdot}9$

TABLE XL.

EFFECT OF HEAT TREATMENT ON THE MODULUS OF ELASTICITY IN TENSION.

Steel.		1·25 per Cent. Nickel. 0·75 per Cent. Chromium. 0·25 per Cent. Carbon.	1·75 per Cent. Nickel. 1·25 per Cent. Chromium. 0·35 per Cent. Carbon.	Air Hardening Nickel, Chromium, Steel. 0·28 per Cent. Carbon, 3·5 per Cent. Nickel, 1·25 per Cent. Chromium.	
Normalising and quenching or air hardening temperature, °C. . .		850	850	820	
MODULUS OF ELASTICITY IN LBS. PER SQ. IN.					
Normalised	—	$29·3 \times 10^6$	$28·7 \times 10^6$	—	—
Water quenched	—	—	—	Air harden	No elastic line
Water quenched and tempered at .	300	—	—	Air harden 300	—
	400	—	—	400	$29·2 \times 10^6$
	500	$29·5 \times 10^6$	$29·1 \times 10^6$	and 500	$29·0 \times 10^6$
	600	$29·1 \times 10^6$	—	600	$29·2 \times 10^6$
	650	—	$29·9 \times 10^6$	tempered at 650	$29·2 \times 10^6$
Oil quenched	—	$29·2 \times 10^6$	—		—
Oil quenched and tempered at . .	300	$29·9 \times 10^6$	—		—
	400	$29·6 \times 10^6$	—		$29·0 \times 10^6$
	500	$29·4 \times 10^6$	$29·7 \times 10^6$		$28·9 \times 10^6$
	600	$29·7 \times 10^6$	$29·3 \times 10^6$		—
	650	—	$29·9 \times 10^6$		$29·2 \times 10^6$
Average		$29·5 \times 10^6$	$29·4 \times 10^6$		$29·1 \times 10^6$

TABLE XLI.

MODULUS OF ELASTICITY IN COMPRESSION OF STEEL HEAT TREATED AT VARYING TEMPERATURES.

Heat Treatment.	Limit of Proportionality. Tons per Sq. In.	Modulus of Elasticity (E). Lbs. per Sq. In.
Heated to 920° C., quenched in water, reheated to 760° C. and quenched in water	13·3	28·9 × 10^6
,, ,, 900° C. ,, ,, ,, ,, ,, ,,	13·6	30·2 × 10^6
,, ,, 880° C. ,, ,, ,, ,, ,, ,,	8·4	29·6 × 10^6
,, ,, 860° C. ,, ,, ,, ,, ,, ,,	4·3	29·4 × 10^6

TABLE XLII.

A COMPARISON OF THE MODULUS OF ELASTICITY IN TENSION AND COMPRESSION ON VARIOUS MATERIALS.

Material.	Kind of Loading.	Limit of Proportionality. Tons per Sq. In.	Yield Stress. Tons per Sq. In.	Ultimate Stress. Tons per Sq. In.	Elongation. Per Cent.	Modulus of Elasticity (E). Lbs. per Sq. In.
Steel forging .	in tension .	16·9	18·5	33·4	36	29·8 × 10^6
	in compression	17·2	19·6	—	—	29·2 × 10^6
Pure nickel bar $\frac{1}{2}$ in. diameter . .	in tension .	5·6	8·4	32·4	52	29·6 × 10^6
	in compression	6·6	8·6	—	—	29·0 × 10^6
Aluminium alloy $\frac{1}{2}$ in. diameter rolled bar	in tension .	11·5	—	21·9	14	10·3 × 10^6
	in compression	9·3	—	—	—	9·8 × 10^6

TABLE XLIII.

TESTS ON BRASS AND PHOSPHOR-BRONZE ROD ¼ INCH DIAMETER.

Analysis per Cent.							Limit of Proportionality. Tons per Sq. In.	Ultimate Stress. Tons per Sq. In.	Extension. Per Cent.	Reduction of Area. Per Cent.	Modulus of Elasticity. Lbs. per Sq. In.
Copper.	Tin.	Lead.	Phosphorus.	Iron.	Zinc.						
95·26	4·28	—	0·14	—	0·32	Phosphor-bronze	12·5	25·4	44·0	63·4	$17·6 \times 10^6$
93·10	6·42	—	0·20	—	0·28	,,	23·8	47·9	20·7	67·0	$14·9 \times 10^6$
60·55	—	0·32	—	0·06	39·07	Brass . .	13·0	40·7	18·7	57·8	$14·5 \times 10^6$
67·24	—	1·30	—	0·44	31·02	,, . .	11·2	31·1	26·7	57·8	$16·8 \times 10^6$
62·14	—	1·49	—	0·03	36·34	,, . .	10·5	29·4	28·0	54·5	$16·0 \times 10^6$

TABLE XLIV.

VALUES OF THE MODULII OF ELASTICITY.

	Tension. Value of "E". Lbs per Sq. In.	Shear. Value of "C". Lbs. per Sq. In.	Volumetric. Value of "K". Lbs. per Sq. In.
Carbon steels	29·5	12·0	—
Nickel steels	28·5	11·2	26·2
Cast iron	14·5 to 18·5	5·1 to 7·7	13·9
Copper (rolled)	15·0	5·6	—
Copper (hard drawn wire)	18·5	7·0	—
Copper (annealed wire)	16·0	6·0	—
Phosphor-bronze	15·0	5·6	—
Aluminium (rolled)	10·2	3·8	10·8
Lead	2·5	0·88	7·2
Tin	7·9	3·0	—
Nickel	29·3	11·2	25·5
Monel metal	26·1	10·0	—
Invar	20·4	—	—
Marble	3·8	—	—
Quartz fibre	7·5	4·4	2·0
Flint glass	7·2 to 8·7	2·9 to 3·6	5·2 to 5·5
Ash	2·2	0·11	—
Spruce	1·5	0·09	—
Mahogany	1·6	0·08	—
Walnut	2·0	0·14	—
Oak	1·3	—	—
Russian fir	2·7	—	—
Hemlock	2·5	—	—
Teak	2·4	—	—

NOTE.—Values are given in millions of lbs. per sq. in., i.e. a value of 29·5 represents 29,500,000 lbs. per sq. in.

§ 139. **Modulus of Transverse Elasticity or Modulus of Rigidity (C).**—The easiest method of determining the value of C is by means of a torsion test. The strain is measured by some form of torquemeter such as is described in § 118.

A stress-strain diagram is drawn in the same way as for the experiments under direct stress, torsional stress as abscissa and torsional strain as ordinate. The value of C is then calculated from the slope of the elastic line. The limit of proportionality in shear is also easily located from the curve.

A series of observations by the N.P.L. mirror torquemeter (§ 118 (iv), p. 180) on a piece of shaft are given in Table XLV and the resultant diagram in Fig. 151.

From this diagram the limit of proportionality in shear is

seen to be with a torque of 1400 lbs.-ins. As the diameter of the test-piece was 0·500 inch this corresponds to a shear stress of

$$\frac{16}{\pi D^3} \times T \text{ lbs. per square inch}$$

where T = external torque in lbs.-inches
D = diameter in inches.

Substituting the proper values of T and D we have limit of proportionality in shear $= \frac{16}{\pi \times (0{\cdot}500)^3} \times 1400$

$= 57{,}400$ lbs. per square inch.

TABLE XLV.

TORSIONAL STRESS-STRAIN OBSERVATIONS.

Diameter of test-piece = 0·500 inch.
Gauge length = 4 inches.

Twisting Moment. Lbs.-Ins.	Torsional Strain.	
	In Torquemeter Units.*	Angle in Degrees.
100	111	0° 19′
200	222	0° 38′
300	329	0° 57′
400	442	1° 16′
500	551	1° 34′
600	656	1° 52′
700	769	2° 12′
800	880	2° 31′
900	989	2° 50′
1000	1103	3° 9′
1040	1145	3° 16′
1080	1190	3° 23′
1120	1233	3° 31′
1160	1278	3° 39′
1200	1322	3° 46′
1240	1369	3° 54′
1280	1403	3° 60′
1320	1446	4° 7′
1360	1497	4° 15′
1400	1550	4° 25′
1500	1699	4° 55′
1600	1919	5° 26′
1700	2249	6° 20′
1800	2859*	7° 58′

* A reading of 2859 = an angle of twist of 7 degrees 58 minutes on a length of 4 inches.

The angle of twist at this torque = 1550 torquemeter uni on a gauge lenth of 4 inches = 4·42° on 4 inches.

$$\text{The strain} = \frac{Da}{2L}$$

where D = diameter in inches
L = gauge length in inches
a = angle of twist in radians.

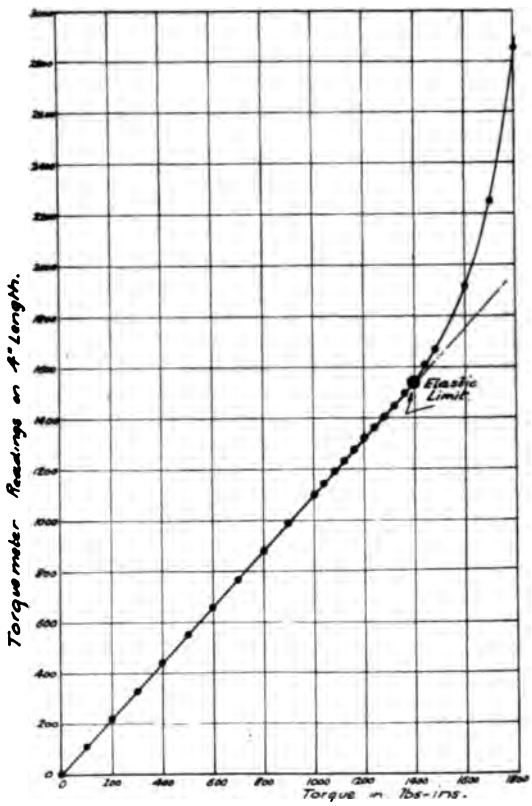

FIG. 151.—Torsional stress-strain curve.

For the case under consideration

$$\text{the strain} = \frac{0{\cdot}500 \times 4{\cdot}42}{2 \times 4 \times 57{\cdot}3} = 0{\cdot}00482.$$

C (modulus of rigidity)

$$= \frac{\text{stress}}{\text{strain}} = \frac{57400}{0{\cdot}00482} = 11{\cdot}9 \times 10^6 \text{ lbs. per square inch.}$$

Instead of calculating the value of "C" from first principles s above, it can be obtained from a formula derived in the ollowing way:—

$$\text{shear stress} = \frac{16}{\pi D^3} \times T$$

$$\text{shear strain} = \frac{Da}{2L}$$

here D, T, a and L represent the same quantities as before.

Therefore $C = \frac{\text{stress}}{\text{strain}} = \frac{16T}{\pi D^3} \times \frac{2L}{aD} = \frac{32TL}{\pi D^4 a}$. equation (1)

If θ° = the angle in degrees

$$\theta^\circ = \frac{180}{\pi} a$$

nd $$C = \frac{32 \times 180}{\pi^2} \times \frac{TL}{D^4\theta^\circ} = 583 \times \frac{TL}{D^4\theta^\circ}$$ equation (2)

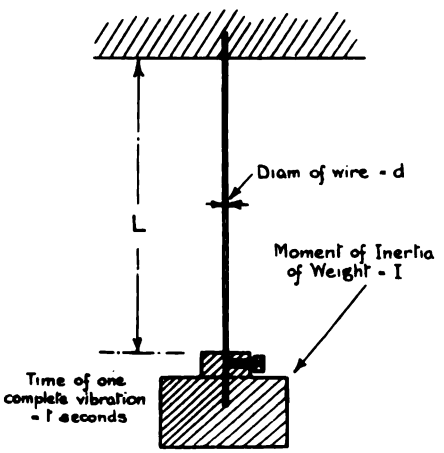

FIG. 151A.

ubstituting the values of T, L, D and θ° in this equation

e have $$C = \frac{583 \times 1400 \times 4}{(0{\cdot}500)^4 \times 4{\cdot}42} \text{ lbs. per square inch}$$

$$= 11{\cdot}9 \times 10^6 \text{ lbs. per square inch.}$$

or wire the value of C is conveniently determined from the me of oscillation of a torsional pendulum. The wire is clamped t its upper end to a substantial frame while its lower end is xed centrally in a relatively heavy weight whose moment of ertia (I) is known. This is indicated in Fig. 151A.

If W/g = the mass of the heavy weight
k = radius of gyration of the weight about its axis of motion

$$I = \frac{W}{g}k^2.$$

If N = the elastic torque required per radian of twist and t = time of one complete (to and fro) vibration in seconds. Then from a consideration of simple harmonic motion

$$t = 2\pi\sqrt{\frac{I}{N}} \text{ and } t^2 = \frac{4\pi^2 \times I}{N}$$

and $$N = \frac{4\pi^2 I}{t^2}.$$

From equation 1 the torque for a twist of angle $a = \frac{C\pi D^4 a}{32L}$

therefore N (torque for twist of 1 radian) $= \frac{C\pi D^4}{32L}$

therefore $$\frac{C\pi D^4}{32L} = \frac{4\pi^2 I}{t^2}$$

or $$C = \frac{4\pi^2 I 32L}{\pi D^4 t^2} = \frac{128\pi IL}{D^4 t^2}.$$

Bauschinger[7] found the value of C for Bessemer steel of carbon content varying from 0·19 per cent. to 0·96 per cent. to range from $11{\cdot}9 \times 10^6$ lbs. per square inch to $12{\cdot}7 \times 10^6$ per square inch.

Platt and Hayward[8] give values varying from $12{\cdot}3 \times 10^6$ lbs. per square inch to $14{\cdot}0 \times 10^6$ lbs. per square inch.

Values of C for various materials are given in Table XLIV, p. 210.

§ 140. **Poisson's Ratio** (see § 7).—Poisson's Ratio is the ratio of lateral to longitudinal deformation and is usually denoted by $\frac{1}{m}$.

An extensometer when used in conjunction with an apparatus for measuring lateral strains, such as are given in § 121, gives the value of $\frac{1}{m}$ for any material in the most direct way possible.

Both instruments are fixed on the test-piece at the same time and measurements are obtained, of both lateral and longitudinal strains, for equal increments of load. The results are then plotted as stress-strain diagrams and the ratio of the slopes of the elastic lines is equal to $\frac{1}{m}$ (Poisson's Ratio).

The figures in Table XLVI are taken from results obtained by Coker.

TABLE XLVI.

MEASUREMENTS OF LATERAL AND LONGITUDINAL STRAINS.

Diameter of the test-piece = 1·01 inch.
Length under test = 8·00 inches.

Load in Lbs.	Lateral Strain Reading.	Longitudinal Strain Reading.
1,000	0	0
3,000	20	34
5,000	42	66
7,000	63	99
9,000	85	132
11,000	106	165

From the plotted values of these results given in Fig. 152 it will be noted that the curves do not pass through the first point but the remainder of the observations lie on straight lines. The slope of the longitudinal stress-strain curve = $408{\cdot}7 \times 10^{-10}$ and the slope of the lateral stress-strain curve = 107×10^{-10}

therefore $$\frac{1}{m} = \frac{107}{408{\cdot}7} = 0{\cdot}262.$$

Average values of Poisson's Ratio for various materials are as given in Table XLVII.

TABLE XLVII.

Material.	Value of Poisson's Ratio.
Glass	0·25
Steel	0·27 to 0·30
Copper	0·33 (0·31 to 0·34)
Brass	0·33 (0·32 ,, 0·35)
Delta metal	0·34
Muntz metal	0·34
Lead	0·43
Stone	0·20 to 0·34
Concrete	0·08 ,, 0·18
Cast iron	0·23 ,, 0·27
Wrought iron	0·27 ,, 0·29

§ 141. **Flexure Method of Determining the Values of E and Poisson's Ratio.**—The method of flexures adopted by Mallock[9] in 1879 has recently been used by Carrington.[10] It is shown diagrammatically in Fig. 153 and consists of a method

for measuring the slope of a flexible beam which is under uniform bending moment. In his tests Carrington uses a beam (A)

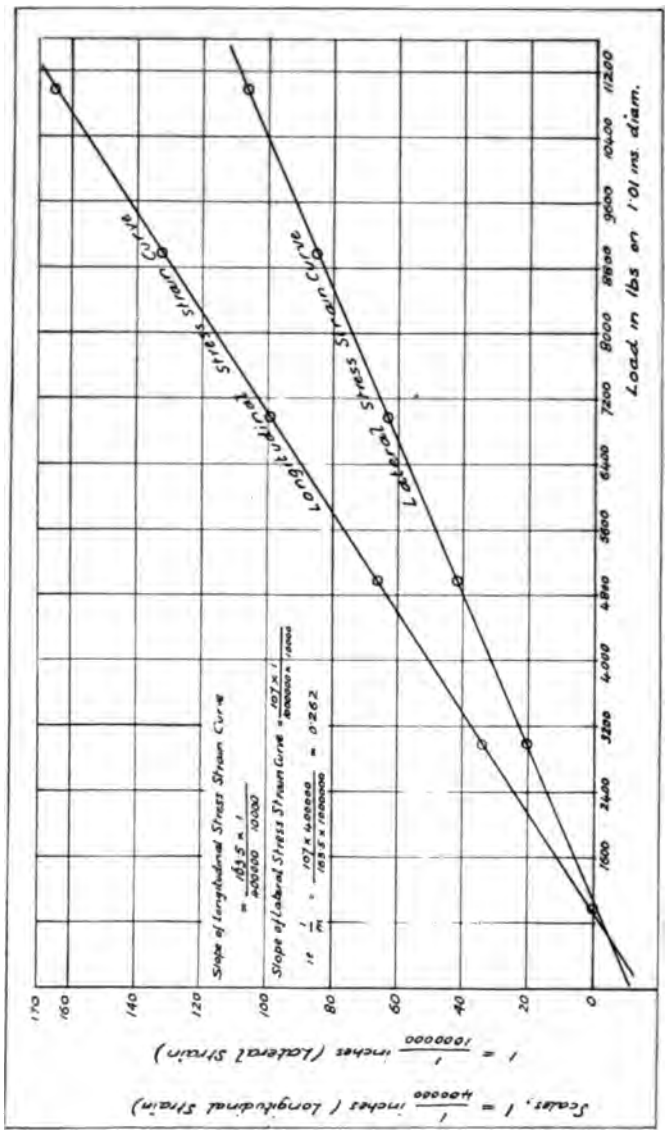
Load in lbs on 1·01 ins. diam.
Longitudinal Stress Strain Curve
Lateral Stress Strain Curve
Slope of Longitudinal Stress Strain Curve = 1/E = 1·97 × 1 / 400000 = 0·262
Slope of Lateral Stress Strain Curve = 1·97 × 1 / 400000 × 1000
Scales, 1 = 1/400000 inches (Longitudinal Strain)
1 = 1/1000000 inches (Lateral Strain)

FIG. 152.—Load-deformation curves for the determination of Poisson's Ratio.

0·750 inch in width and 0·130 inch deep. This is supported on knife edges having a span of 12 inches, with the central 8 inches

under uniform bending moment applied by means of weights hanging from D and E.

Mirrors F_1 and F_2 are attached to small columns G_1K and G_2L fixed to tbe beam at K and L.

Satisfactory dimensions for these parts are :—

$$\begin{cases} KL &= 1 \text{ inch} \\ G_1K &= 2\tfrac{1}{2} \text{ inches} \\ G_2L &= 1\tfrac{1}{2} \text{ inch.} \end{cases}$$

A scale (S), at a mean distance from the mirror = L, is viewed in a telescope (T), the scale being reflected from the mirror F_2 to the mirror F_1 and thence to the telescope as indicated.

The modulus of elasticity $(E) = \dfrac{24a\left(L + \frac{c}{2} + \frac{a}{2}\right)}{bd^3}\left(\dfrac{M}{x}\right)$

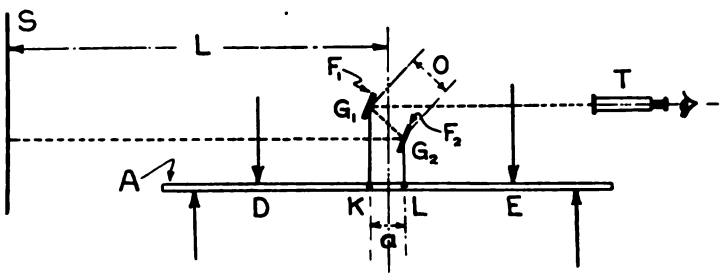

FIG. 153.—Method of flexures.

where b = breadth of the beam
d = depth of the beam
a = distance between the mirror columns = KL
c = distance between the mirrors = G_1G_2
L = scale distance.

For determinations of Poisson's Ratio ; it is necessary to obtain the lateral curvature, and this is done by the same method. The axes of the columns, telescope and scale being, in this case, in a plane at right angles to the axis of the beam and at the mid-point of the span

Curves are plotted connecting bending moment and scale reading for both directions of curvature, these curves are straight and the ratio of their slopes gives the value of Poisson's Ratio. If the lengths of a and L are not the same for both directions, a correction must be applied to the result to allow for the difference in the values.

The method is only applicable for beams in which the sizes of the breadth, depth and span are in approximately the same ratio as used by Carrington.

Care should be taken to see that the knife edges are curved to allow for lateral curvature of the beam and also that the specimen cannot rotate.

Results obtained on five materials by this method together with those found by the standard tension and torsion methods on the same materials are given in Table XLVIII.

TABLE XLVIII.

	Steel.	Wrought Iron.	Brass.	Copper.	Aluminium.
"E" by flexure method	28·1	27·9	14·2	17.6	9·23
"E" from tension test .	28·3	28·3	14·0	17·9	9·30
"C" from torsion test .	11·2	10·8	5·41	6·80	3·49
Poisson's Ratio from flexure test . . .	0·236	0·245	0·333	0·305	0·313
*Poisson's Ratio by calculation from E and C in tension and torsion test	0·255	0·290	0·310	0·295	0·320

The values given in the table are in millions of lbs. per sq. in.
E = modulus of direct elasticity.
C = modulus of rigidity.

*Poisson's Ratio $= \frac{E}{2C} - 1$.

REFERENCES FOR CHAPTER XIII.

[1] Rasch, "Proc. Int. Assoc. Test. Mat.," 1909, Article VII 3.
[2] Muir, "Roy. Soc. Phil. Trans.," Vol. CXCIII, p. 1, 1900.
[3] Stanton Walker, "Modulus of Elasticity of Concrete," "Proc. Amer. Soc. Test. Mat.," Vol. XIX. 1919, p. 512.
[4] Goodrich, "Concrete Steel Construction" (translation of Morsch's "Der Eisenbetonbau").
[5] Marshall, "Amer. Soc. Civ. Eng. Trans.," Vol. XVII, p. 62.
[6] Brinell, "Proceedings Iron and Steel Inst.," Vol. LX, p. 234.
[7] Bauschinger, "Civilingenieur," 1879.
[8] Platt and Hayward, "Inst. Civ. Eng. Proc.," Vol. XC, p. 409.
[9] Mallock, "Roy. Soc. Proc.," 1879. Vol. XXIX.
[10] Carrington, "Determination of the Value of E and Poisson's Ratio by the Method of Flexures," "Phil. Mag.," Feb. 1921, Vol. XLI, p. 206.

CHAPTER XIV.

EXPERIMENTS ON THE REPETITION OF STRESSES.

§ 142. IT has been shown by experiment that materials fail under stresses considerably lower than the ultimate when those stresses are repeated many times.

Stanton and Bairstow[1] have shown microscopically that this deterioration is due to "slip lines being set up at the point of maximum stress in the cleavage planes of the crystals and due to unequal distribution of stress among the crystals". These slip lines broaden out and develop into actual cracks under a repetition of stress. This type of failure is sometimes called "fatigue" but is perhaps better described as a "repeated stress failure".

In many cases the stress does not alternate between zero and a maximum in tension, there may be an initial tensile or initial compressive stress. For the purpose of a consideration of this subject compressive stress is taken as a negative tensile stress and the range of stress as the difference between the maximum and minimum stresses.

Alternating stresses are usually considered as being those in which the maximum and minimum stresses are equal but of opposite sign.

Since 1864, when Fairbairn published results in the "Roy. Soc. Phil. Trans." on riveted wrought-iron girders subjected to repeated stresses, many important researches on this subject have been undertaken. As a result of his work, Fairbairn recommended that the safe repeated stress should be not more than one-third of the ultimate stress.

In 1871 Wöhler published the results of an exhaustive series of repeated stress experiments in direct stress, bending and torsion which had been carried out during the previous twelve years. A full description of these tests is given in "Engineering" of 1871 and a good account by Unwin.[2] The most important

deductions from these experiments on wrought iron and steel are:—

(*a*) A stress below the ultimate stress will fracture wrought iron and steel if it is repeated many times.

(*b*) The range of stress and not the maximum stress determines, within certain limits, the number of repetitions before fracture.

(*c*) For a given maximum or minimum stress the number of repetitions before fracture increases as the range of stress is diminished and there is a range of stress called the *limiting range* at which the number of repetitions is infinite.

(*d*) The limiting range of stress diminishes as the maximum stress increases.

Wöhler's work was continued on the same machines and confirmed by Spangenberg whose results, however, were not so consistent as the original work by Wöhler.

Results published in 1886 by Baker,[3] who had experimented with soft and hard steel (28 and 54 tons per square inch respectively) and 27 ton rivet iron, were in complete agreement with Wöhler's researches.

A considerable number of experiments on the effect of varying values of the minimum stress on the limiting range of stress have been carried out by Haigh.[4]

In 1915 he reported a series of tests on mild steel to the British Association. These are summarised in Table XLIX.

TABLE XLIX.

REPEATED STRESS TESTS ON MILD STEEL.

Ultimate Static Stress, Tons/Sq. In.	Limiting Minimum Stress, Tons/Sq. In. A.	Limiting Maximum Stress, Tons/Sq. In. B.	Limiting Range of Stress, Tons/Sq. In. B-A.
26·0	+ 4·05	+ 21·55	17·5
	− 0·88	+ 20·62	21·5
	− 7·3	+ 17·20	24·5
	− 13·0	+ 13·00	26·0
	− 16·96	+ 6·54	23·5
	− 20·10	+ 1·40	21·5
	− 21·95	− 2·45	19·5

The results are plotted in Fig. 154 from which it is seen that:—

(1) When the minimum stress is zero, the range of stress is approximately 21·0 tons per square inch, i.e. a tensile stress of

80 per cent. of the ultimate stress is sufficient to fracture the material when repeated a considerable number of times.

(2) When the minimum stress is less than half of the range (i.e. from 4·05 to − 13·0) the curve approximately follows Gerber's parabola (see § 144), otherwise there is a noticeable deviation from the parabolic form.

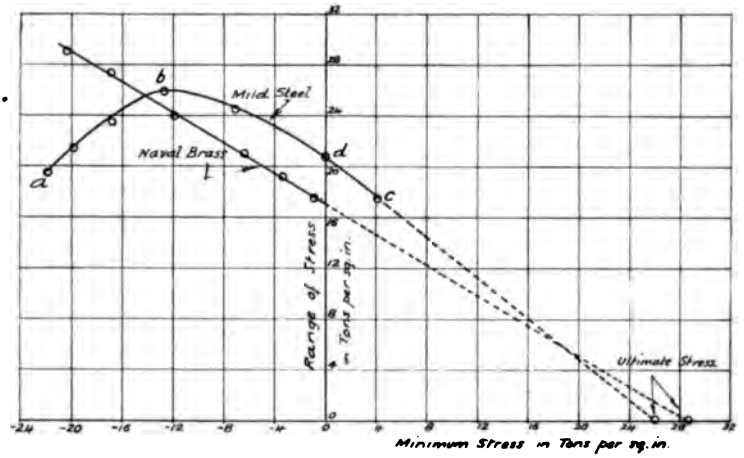

FIG. 154.—Repeated stress tests on mild steel and naval brass (Haigh).

TABLE L.

ALTERNATING STRESS TESTS ON MILD STEEL.

Ultimate Stress (Static). Tons/Sq. In.	Alternating Stresses (Equal Tension and Compression).	
	Range of Stress. Tons/Sq. In.	Millions of Cycles to Fracture.
26·0	39·3*	0·003
	32·7	0·08
	31·3	0·056
	31·3	0·16
	29·9	0·19
	29·9	0·80
	28·8	0·41
	28·7	1·01
	27·5	1·37
	27·5	2·18
	26·4	1·66
	26·4	5·90
	25·4	7·20 unbroken
Limiting range of stress = 26·0 tons per sq. in. * 39·3 (range) = + 19·65 to − 19·65		

Results in Table L give details of the observations on mild steel when the stresses are alternating (i.e. equal tension and compression). These confirm Wöhler's deductions (*b*) and (*c*).

Tests on naval brass by Haigh are summarised in Table LI and plotted in Fig. 154 and show that for the brass under consideration the equation connecting minimum stress and range of stress is that of a straight line passing through the point where the minimum stress is equal to the ultimate stress.

Haigh says that, as a rule, metals which give a considerable reduction of area at fracture have a high value of the ratio of alternating stress range (with equal tension and compression) to the ultimate stress. This usually varies between 1·20 in ingot iron and the best mild steel, and 0·80 in high tensile and tool steels in the annealed condition.

TABLE LI.

REPEATED LOADING TESTS ON NAVAL BRASS.

Ultimate Stress (Static). Tons/Sq. In.	Limiting Minimum Stress. Tons/Sq. In. A.	Limiting Maximum Stress. Tons/Sq. In. B.	Limiting Range of Stress. Tons/Sq. In. B-A.
28·7	− 1·0	+ 16·5	17·5
	− 3·4	+ 15·8	19·2
	− 6·5	+ 14·5	21·0
	− 12·0	+ 12·0	24·0
	− 17·0	+ 10·5	27·4
	− 20·5	+ 8·5	29·0

Results of tests carried out by J. H. Smith[5] on the machine described in § 148 are also in agreement with those obtained by Wöhler and Haigh.

Table LII, taken from an extensive series reported by J. H. Smith, gives the results of experiments on a 3¼ per cent. nickel steel when using different values of the minimum stress. Two methods were used for obtaining these results.

(*a*) An endurance method (§ 145).

(*b*) The yield range method (§ 162).

The results by both methods are plotted in Fig. 155 and are seen to be in very good agreement.

TABLE LII.

REPEATED LOADING TESTS ON 3½ PER CENT. NICKEL STEEL BY J. H. SMITH.

Limiting Minimum Stress. Tons per Sq. In.	Limiting Maximum Stress. Tons per Sq. In.	Limiting Range of Stress. Tons per Sq. In.	Method of Test.
− 19·4	+ 19·4	38·8	Endurance Method
− 8·8	+ 26·2	35·0	
0	+ 27·8	27·8	
+ 5·7	+ 28·3	22·6	
− 30·4	− 8·0	22·4	Yield Range Method
− 28·5	+ 0·2	28·7	
− 26·9	+ 5·7	32·6	
− 24·4	+ 11·8	36·2	
− 20·2	+ 20·2	40·4	
− 11·8	+ 24·4	36·2	
− 5·7	+ 26·9	32·6	
− 0·2	+ 28·5	28·7	
+ 8·0	+ 30·4	22·4	

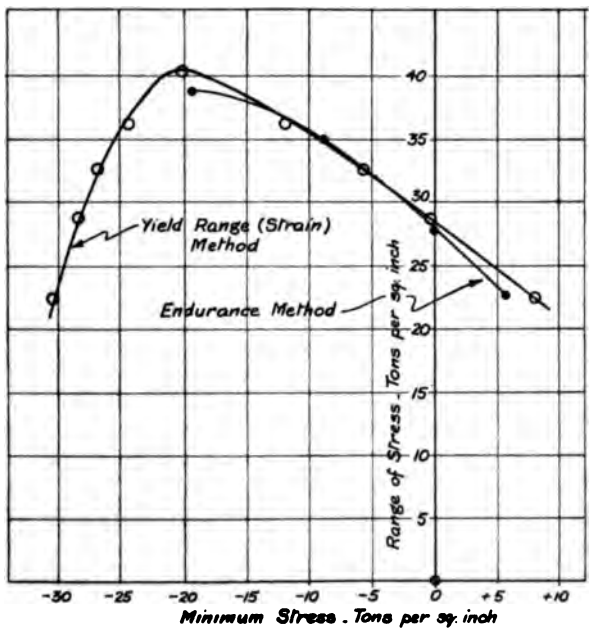

FIG. 155.—J. H. Smith's repeated stress results on 3½ per cent. nickel steel.

§ 143. **Bauschinger's Theory of Failure.**—Bauschinger's theory of failure due to repeated stresses is the only one which

has received serious consideration. He shows that, with bars subjected to cyclical variations of stress, the elastic limits in tension and compression take up new positions. The range between the two limits depending on the material and the stress at the lower limit of elasticity. Thus if the elastic limit is raised in tension by overstrain it is simultaneously lowered in compression so that for that condition of loading two new limits are set up which Bauschinger calls the *natural* elastic limits. He showed, further, that the range between these limits was the same in magnitude as the maximum range of stress which could be applied to the material an infinite number of times without causing fracture.

Bairstow,[6] in an important paper communicated to the Royal Society from the National Physical Laboratory, has given experimental results which constitute the first strong support of Bauschinger's hypotheses.

In the testing machine used by Bairstow for the purpose of the experiments, cyclical variations of direct stress are automatically produced at the rate of two per minute. The extensometer, which is of the Martens mirror type, is fixed to the specimen throughout the test, and in this way the whole history of the progress of fatigue is observed.

When the limits of stress are tension and compression of equal values it is found that, if the range of stress is above a definite value, the stress-deformation curve forms a closed loop, which is called the hysteresis loop, consisting of two parallel straight lines, corresponding to the variation of stress from the limits of stress towards the mean stress, and two curved portions, corresponding to the variations of stress from the mean value to the extreme values (Fig. 156). The width of this loop, which is the permanent set of the specimen per cycle, increases as the range of stress increases, but for a definite range of stress tends to a limit which is not greatly exceeded by subsequent repetitions of loading, even when this is the range at which fracture under fatigue eventually takes place. Under these conditions of stress the mean length of the specimen remains constant.

When the limits of stress are unequal the hysteresis loop is formed as before but is not closed, owing to the fact that the mean length of the specimen gradually changes because of the continued repetition of the same cycle of stress, i.e. the change of mean length of the specimen per cycle is the amount by which the hysteresis loop is enclosed. The amount of the permanent extension during the earlier stages of the breakdown becomes

considerable as the superior limit of stress approaches the static yield point, and if its value, after the first considerable stretch has occurred, be plotted against the corresponding values of the superior limit, it is found that the curves gradually come into coincidence with the ordinary static "stress-elongation" curve at the yield point. FEABC (Fig. 157) shows such a curve, in producing which no cyclical variations of stress are concerned.

The principal conclusions arrived at by Bairstow are summarised thus:—

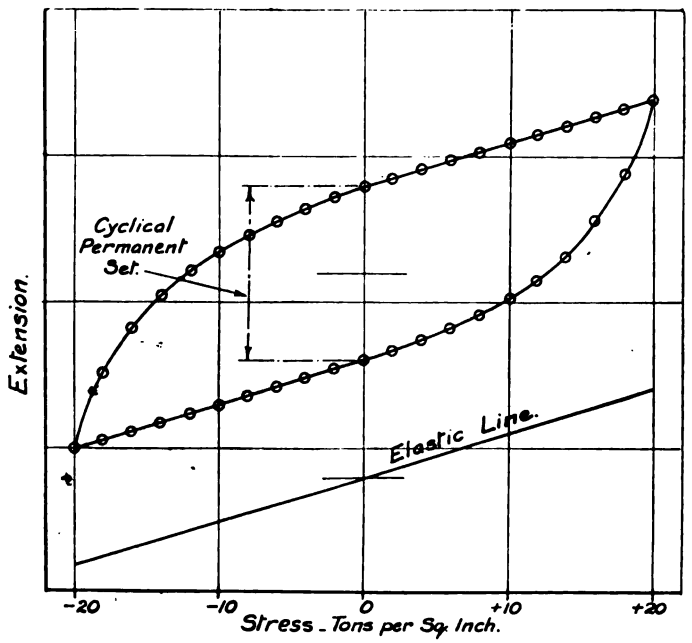

FIG. 156.—A typical hysteresis loop.

(*a*) The "natural elastic range" is the value to be used in design, and, with equal compressive and tensile stresses, this value is identical with the "Wöhler safe range".

(*b*) The natural elastic range depends upon (1) the material and (2) the lower limit of stress. The elastic range when the lower limit is zero is less than that with equal tensile and compressive stresses (about 15 per cent. with axle steel and 6 per cent. with Bessemer steel).

(*c*) If a load-extension curve is plotted, the extension being the value of the permanent extension reached after repeated

alternations, it assumes the form found with hard drawn copper wire, which has no yield point but corresponds with the curve FEJHBC, of Fig. 157, produced back to the "natural" elastic limit.

(*d*) Recovery due to stoppage of the alternations of stress is appreciable, being somewhat rapid for some materials. Recovery reduces the permanent extension at a given load and can be greatly accelerated by immersing in boiling water for a few minutes, as suggested by Muir.[7]

If an inclined line e_1a (Fig. 158) is taken to represent the

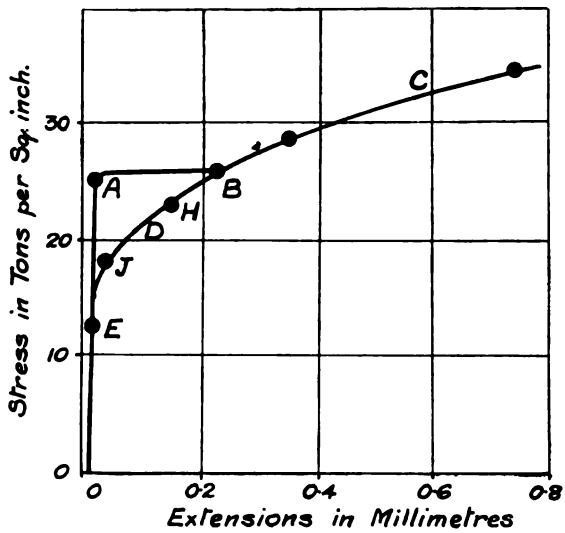

FIG. 157.—Force-elongation diagram.

limiting minimum stresses and the limiting maximum stress corresponding to each limiting minimum stress is plotted on the corresponding ordinate a curve of maximum stress *ea* is obtained. The vertical distance between the two curves represents the limiting range of stress and it will be observed:—

(1) That as the limiting minimum stress increases the range decreases.

(2) That if both the maximum and minimum stress applied to the material fall between the two curves then the material will not fail under a repeated stress having these maximum and minimum values.

§ 144. **Formulæ for Repeated Stresses.**—Various empirical formulæ have been suggested to connect the limiting values of the maximum, minimum, and range of stress.

(*a*) **Weyraugh and Launhardt's Formulæ.**—

If $f_{max.}$ = limiting maximum stress.
$f_{min.}$ = limiting minimum stress.
f = ultimate static stress.
Z_1 = limiting range of stress when $f_{min.} = 0$.
$2Z_2$ = limiting range of stress when $f_{min.} = -f_{max.}$

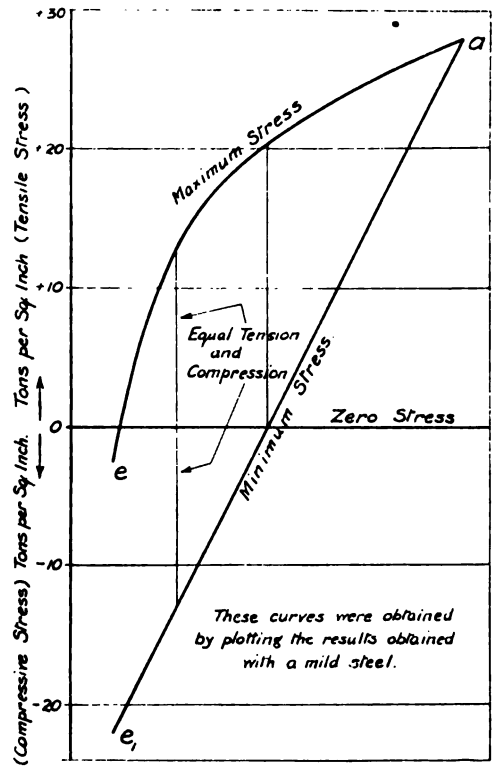

FIG. 158.—Curves connecting limiting minimum and maximum stress.

Weyraugh [8] suggested the formula :—

$$f_{max.} = Z_1 - \frac{f_{min.}}{f_{max.}}(Z_1 - Z_2)$$

here the stress is wholly or partly reversed.

Launhardt suggested the formula :—

$$f_{max.} = Z_1 + \frac{f_{min.}}{f_{max.}}(f - Z_1)$$

where the stress is applied without reversal.

Fig. 159 is drawn plotting the values of $f_{max.}$ from the above formulæ assuming the values of $f_{min.}$ to lie on the inclined line RS and :—

$$Z_1 = f/2 \text{ and } Z_2 = f/3$$

The latter have been found to be average values for a variety of materials.

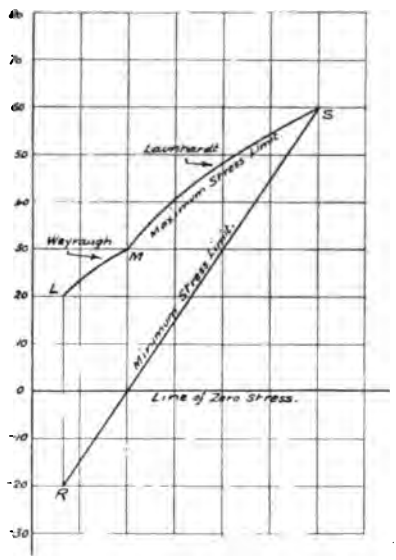

FIG. 159.—Curves for Weyraugh and Launhardt's formulæ.

The curved line for the maximum stress limit derived from Weyraugh and Launhardt's formulæ is sometimes assumed to be straight in which case one formula covers the whole field of repeated stresses.

(*b*) **Gerber's Parabolic Relation.**—Gerber showed that by plotting the limiting minimum stress as abscissa and the corresponding safe range as ordinate, a curve was obtained which, to a first approximation, was parabolic.

Using the previous notation Gerber's parabolic relation is expressed by the formula

$$f_{max.} = \frac{f_{max.} - f_{min.}}{2} + \sqrt{f^2 - nf(f_{max.} - f_{min.})}$$

n being a constant for the material.

§ 145. **Repeated Stress Testing Machines.**—All Wöhler's tests were carried out at a speed of less than 100 reversals per minute and a determination of the fatigue range occupied a very long time.

Various machines have been constructed to accelerate the test.

Before describing those machines which are in constant use for this branch of testing, it is advisable to explain the usual procedure which is adopted in the determination of the limiting range of stress.

Starting with an unknown material and a machine giving 2000 reversals per minute two methods of attacking the problem are used.

(*a*) If the amount of the material is small and only a limited number of test-pieces can be prepared, a low range is applied to the first test-piece which is increased by about 30 per cent. after ten million reversals. Increments of the same value are added to the stress range after each additional ten million reversals until the test-piece fails. (If the test-piece is hollow the number of reversals can be reduced to five million.) The range is then known to be between two values (assuming the material to be homogeneous). A second test-piece is then inserted in the machine and a range applied slightly higher than the lower of the two previous values. This range is increased by small increments (depending upon the accuracy with which the results are desired) after each ten million reversals until failure occurs.

(*b*) Where at least four test-pieces are available, the limiting range is approached from the opposite direction. The first test-piece has a high range of stress applied to it and from the number of reversals required to fracture an estimate can be obtained as to the probable range. The next specimen is tested under a range still believed to be on the high side and this process is repeated until a range is obtained under which the material does not break. A stress-reversals curve can then be drawn from which the range of stress can be estimated with whatever accuracy is required consistent with the homogeneity of the material.

The method of procedure adopted will depend on :—

(*a*) The amount of material available.

(*b*) The relative cost of preparation of test-piece and running of the testing machine.

(*c*) The importance of the time of duration of test.

With machines of higher speed than 2000 reversals per minute it is usually considered that a larger number of reversals is required in order to be satisfied that, if the test-piece does not break, the range applied is within the safe range.

Various quick methods of test, depending on small but definite yielding of the material, have been devised by C. E. Stromeyer, J. H. Smith, and recently at the National Physical Laboratory. These are described in §§ 158-162.

The machines which are in common use can be divided into four main types:—

(1) Rotating cantilever machines.

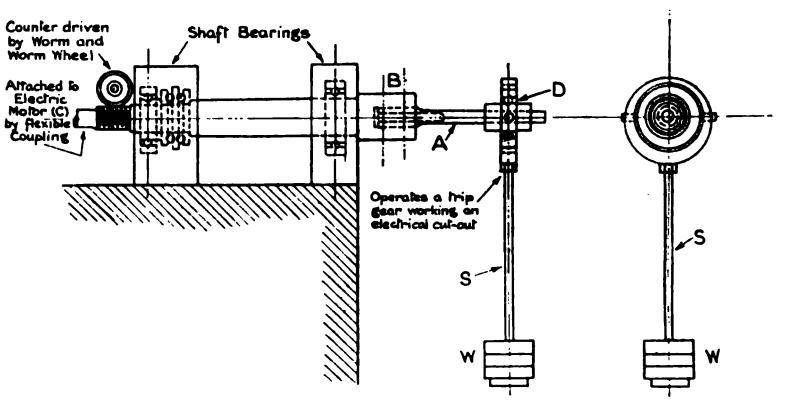

FIG. 160.—Rotating cantilever fatigue machine (Wöhler type).

(2) Rotating bar machines with a short length under a constant bending moment.

(3) Direct stress machines. Load applied by an unbalanced revolving weight.

(4) Direct stress machines. Load applied by the pull of an electro-magnet excited by an alternating current.

§ 146. **Rotating Cantilever Machines for Reversals of Bending Stress.**—This type of machine has been run successfully at 3000 revolutions per minute and is shown diagrammatically in Fig. 160. It consists of a test-piece (A) held in a rotating chuck (B) driven either direct or through gearing by an electric motor (C). The test-piece is loaded by weight (W) on a scale pan (S) which is attached to the test-piece through the

FIG. 161.—Wöhler fatigue testing machine.

[*To face p.* 231.

ball-bearing (D). The connection between the ball-bearing and the scale pan is such that the latter can adjust itself in a vertical direction without putting any constraint on the ball-bearing.

The number of alternations is recorded by a counter driven by a worm-wheel from a worm cut on the machine shaft. The breaking of the test-piece usually operates a switch and stops the motor; by this means the machine can be run continuously with but little attention.

A slight modification of the counting and stopping method is, in some cases, adopted. The counter is attached to the ball-bearing holder (by which the load is applied) and is driven by the inner race of the ball-bearing. The breaking of the test-piece causes the counter to cease recording and the machine continues to run, without a test-piece, until the next inspection.

A rotating cantilever machine which has been running successfully at the National Physical Laboratory is shown in Fig. 161.

With a bending test, the stress distribution over the cross section is unknown if the elastic limit is exceeded and the maximum stress only falls on the outer fibres of the test-piece. The test-piece is often made hollow as in Fig. 162; the part under test being only a thin shell.

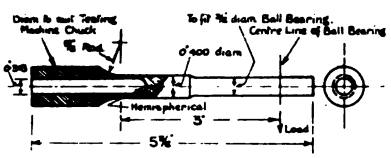

FIG. 162. — Hollow Wöhler alternating stress test-piece.

Machines of the rotating cantilever or Wöhler type have been used for researches described by Wöhler,[10] Stead and Richards,[11] C. B. Dudley,[12] F. Rogers,[13] Stanton and Pannell,[14] J. O. Roos,[15] C. E. Stromeyer,[16] and A. Martens.[17]

They are made commercially by Alfred J. Amsler & Co. and Tinius Olsen Testing Machine Co. The latter company call them "White-Souther Endurance Testing Machines".

§ 147. **Rotating Bar Machines.**—This type of machine was first used by Sondericker[18] in 1892. The method of test is shown diagrammatically in Fig. 163. The test specimen (ABCD) is subjected to a uniform bending moment while revolving on its axis. It is supported on swivelling bearings at "A" and "D" and the central portion between "B" and "C" is reduced in diameter. The maximum stress ($f_{max.}$) on the test-piece is calculated from the formula

$$f_{max.} = \text{bending moment} \times \frac{32}{\pi d^3}$$

where d = the diameter of the reduced portion.

Besides Sondericker this method of test has been used by J. E. Howard,[19] Eden, Rose and Cunningham[20] and Akimasa Ono.[21] Prof. Akimasa Ono uses his machine for tests in combined bending and torsion (see § 156).

A useful little machine of the Sondericker type, shown in Fig. 164 and made by W. & T. Avery, Ltd., enables two specimens to be tested at the same time. The test-pieces (T_1, T_2) are secured at each end in suitable sockets which are attached to ball-bearings, (B_1, B_2). The ball-bearings are mounted on axes which are horizontal but perpendicular to the principal axis of the machine and are driven through double universal joints. This enables the machine to run smoothly when the test-piece becomes

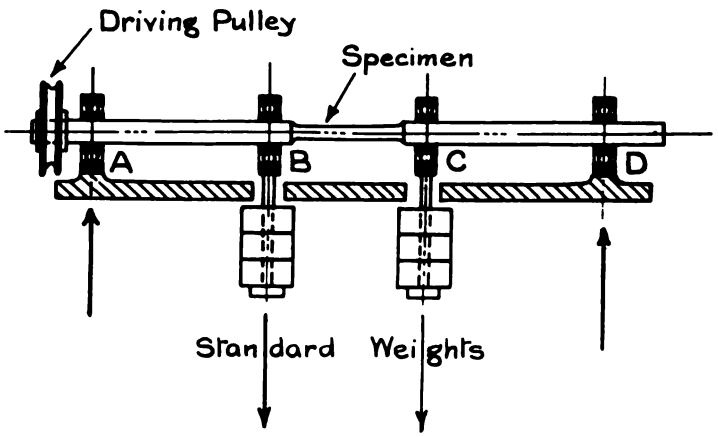

FIG. 163.—Rotating bar fatigue machine (Sondericker's method).

bent elastically, due to the loading. The loading gear is mounted on the middle portion of the specimen and comes between the ball-bearings in which the specimens rotate. Two ball-bearings are provided, one for either side of the middle of the specimen, the load being applied through the shackle and links in the manner shown. On the breaking of the specimen at the end of the test, the links holding the shackle are caught by the casting on the main standard. The ball-bearing carried by the outer broken half of the specimen falls, putting the counter mechanism out of action. As this ball-bearing falls it is forced by an inclined plane on the links away from the centre of the machine. The two broken ends of the specimen are thus parted and prevented from grinding on one another. The straining gear is designed

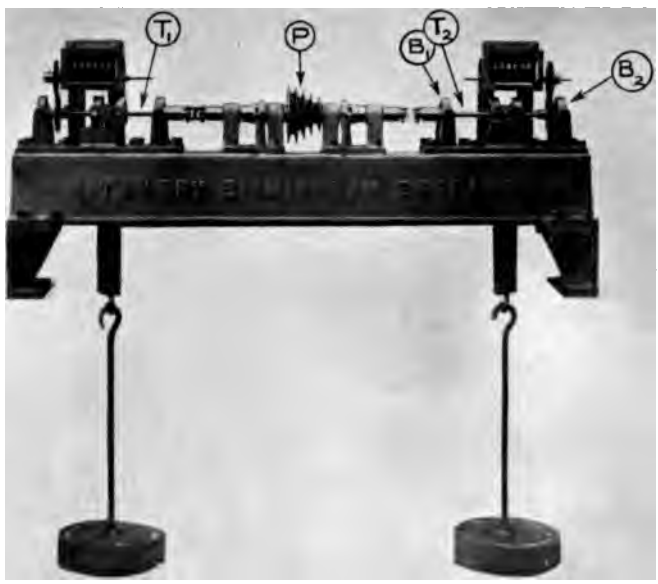

FIG. 164.—Avery's rotating bar fatigue machine.

[*To face p.* 232.

to put a fibre stress on the specimen from 1000 to 100,000 lbs. per square inch, the dead weights supplied with the machine permit increments of stress of 1000 lbs. per square inch throughout the whole range of the apparatus.

The machine is driven by a set of grooved pulleys (P), mounted on a steel spindle, which is carried by the two headstocks of the machine.

§ 148. **Direct Stress Machines.**—Load applied by an unbalanced weight.

In 1902 Osborne Reynolds and J. H. Smith[22] described a throw testing machine for reversals of stress in simple direct stresses which were produced on a test-piece by the inertia forces

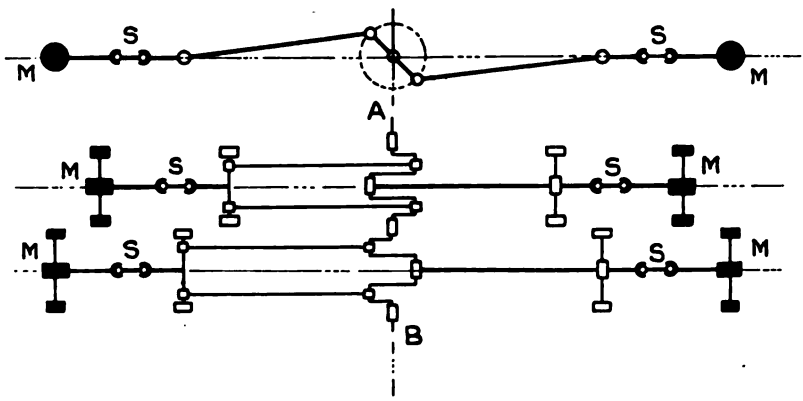

FIG. 165.—Diagram of Stanton's alternating stress testing machine.

of reciprocating weights driven by a crank and connecting rod from a rotating shaft.

A machine of the same type was designed by T. E. Stanton[23] and used for his work on the resistance of iron and steel to reversals of direct stress. A diagram of the mechanism is shown in Fig. 165, which also explains the method of balancing the cranks.

Four masses (M) reciprocating horizontally are operated by four cranks (C). There are therefore two independently perfectly balanced systems with cranks set 180° apart on the same shaft (AB). The cranks of one system are at right angles to the cranks of the other system so that the kinetic energy of the moving parts is thus approximately constant. There are four test-pieces (S), one stressed by each reciprocating mass.

J. H. Smith's [b] improved type of direct stress machine is shown in Fig. 166. A definite range of stress is imposed on the test-piece by the use of unbalanced flywheels and mean stress is added by means of a calibrated spring.

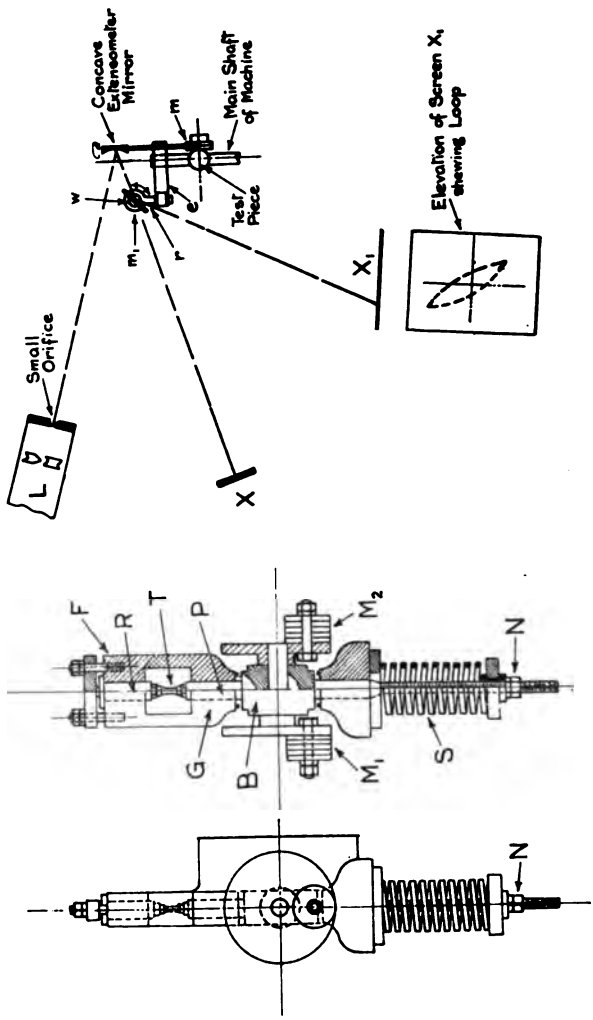

Fig. 166.—J. H. Smith's direct stress machine.

The upper end of the test-piece (T) is bolted to the guided rod R which in turn is fixed to the frame F of the machine. At its lower end the test-piece is locked to another guided rod (P)

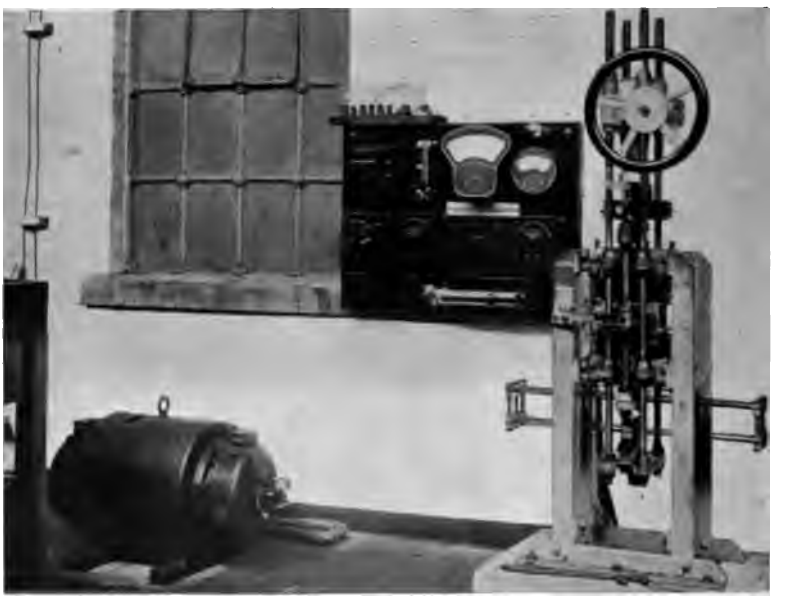

FIG. 167.—Haigh repeated stress machine installed at the N.P.L.
[*To face p.* 235.

which is formed with an enlarged piece (B) having a bearing, at right angles to the axis of the machine, for the rotating masses M_1 and M_2. The lower guided rod (P) is made square in the under guide (G) in order to prevent rotation and is continued through the spring (S). At its lower end it has a tightening nut (N) by means of which the spring can be compressed and any desired initial stress applied to the specimen.

An alternating load is applied by the longitudinal components of the centrifugal force of the rotating masses, M_1 and M_2, which are driven at the desired speed through a special form of coupling arranged to prevent any of the driving force being communicated to the test-piece. To prevent an unknown initial stress, the specimen is locked in the guiding rods (P and R) before the upper rod (R) is rigidly connected to the frame.

Machines of this type, however, suffer from the disadvantage that the inertia forces vary with the square of the speed. It is therefore necessary to control the speed very carefully if reliable results are expected.

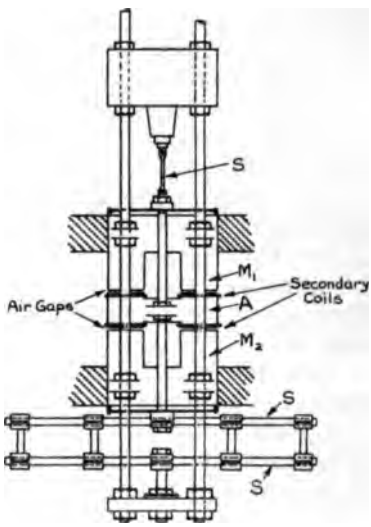

FIG. 168.—Diagram of Haigh's repeated stress machine.

§ 149. **Direct Stress Machines.**—Load applied by pull of an electro-magnet excited by an alternating current.

This method has been successfully applied by G. Kapp,[24] B. Hopkinson,[25] and B. P. Haigh.[26]

Haigh has introduced several new features into his latest design. Fig. 167 shows a machine installed at the N.P.L. and Fig. 168 illustrates the principle adopted.

The test-piece is connected at its upper end to the frame of the machine in such a way that its height can be adjusted to allow for elongation, while the lower end is attached to a frame carrying the armature (A) of a two-phase electro-magnet (M_1 and M_2).

The electro-magnet is excited by an alternating current from a generator giving a sign wave E.M.F. so that the pull is

almost proportional to $\left(\frac{\text{voltage}}{\text{frequency}}\right)^2$, nearly independent of the air gap which is small, and pulsates with twice the frequency of the electric current.

Two small secondary coils wound on frames are fixed close to the pole faces and the voltage induced in these coils is measured by a voltmeter and used for calculating the stress.

In order that the pull of the two magnets shall be of the same amount it is necessary that the air gaps shall be equal. A fine adjustment is provided with the machine to enable the test-piece frame and armature to be raised or lowered during a test until the current in the two coils, and therefore the air gaps, are equal. The coils are connected to a differential ammeter which reads zero when this condition is fulfilled.

By the use of a choking coil the voltage readings are rendered nearly independent of the frequency over a fairly large range so that slight alterations of frequency during a test do not alter the range of stress.

The frame carrying the test-piece and armature is also attached, below the latter, to standard springs (SS). The stiffness of these springs is adjusted to counterbalance the inertia of the armature, etc., a precaution which is very desirable as it eliminates a correction which would amount to 5 per cent. of the stress range. This adjustment is effected by setting the springs so that the moving system, without the test-piece in place, vibrates in resonance with the magnetic pull.

By extending or compressing the springs an initial pull or push can be applied to the test-piece so as to alter the magnitude of the minimum stress.

Thus if f_e = the alternating stress applied electro-magnetically
and f_s = the stress applied by the springs,
then the maximum stress $(f_{\text{max.}}) = f_e + f_s$,
and the minimum stress $(f_{\text{min.}}) = -f_e + f_s$.
Range of stress $= Z = f_{\text{max.}} - f_{\text{min.}} = f_e + f_s + f_e - f_s$
$= 2f_e$.

i.e. the range is not affected by the load applied by the springs.

The voltmeter is calibrated by measuring the range of stress (photographically) by a special form of optical extensometer. This is shewn diagrammatically in Fig. 169.

§ 150. **Vibration Method for the Determination of the Fatigue Range for Flat Springs.**—On hardened and tempered springs out of which test-pieces cannot be cut for the standard

fatigue machines, a vibratory method is sometimes employed. The arrangement adopted at the National Physical Laboratory is as follows. The spring (S) to be tested (Fig. 170) is clamped to a rigid support (C) and carries at its outer end a bearing (B) in which an unbalanced shaft (P) can rotate. This shaft is driven through a helical spring (R) by an electric motor (M) provided with a speed regulator. On starting the test the motor speed is gradually increased until the disturbing force due to the unbalanced shaft sets up a vibration of the required amplitude of the spring to be tested.

The amplitude is calculated from the range of stress on the section XX under which the material is to be tested and is

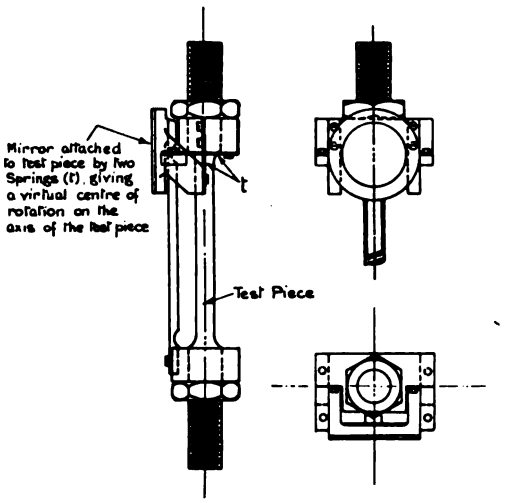
Mirror attached to test piece by two Springs (t), giving a virtual centre of rotation on the axis of the test piece
t
Test Piece

FIG. 169.—Optical extensometer for calibrating Haigh's testing machine.

measured by the movement of a spot or line of light reflected from a mirror fixed on the bearing (B) at a known distance from XX.

§ 151. **Effect of Speed on the Limiting Range of Stress.**—Reynolds and Smith [22] found that the limiting range of stress was smaller at speeds of 1300 to 2500 per minute than at 60 to 80 cycles per minute. Their conclusions have not, however, been confirmed by subsequent experiments.

Stanton and Bairstow [1] using a machine of the same type found that a change of speed from 60 to 800 did not seriously affect the range, and later, using a machine of the same type

as Wöhler, they found that there was no evidence at all of any reduction in fatigue strength due to a rate of alternations of 2200 when compared with 200.

With respect to Reynolds and Smith's results Stanton says, " It seems probable that the reduction in fatigue strength noted by Reynolds and Smith as due to high rate of alternations is a

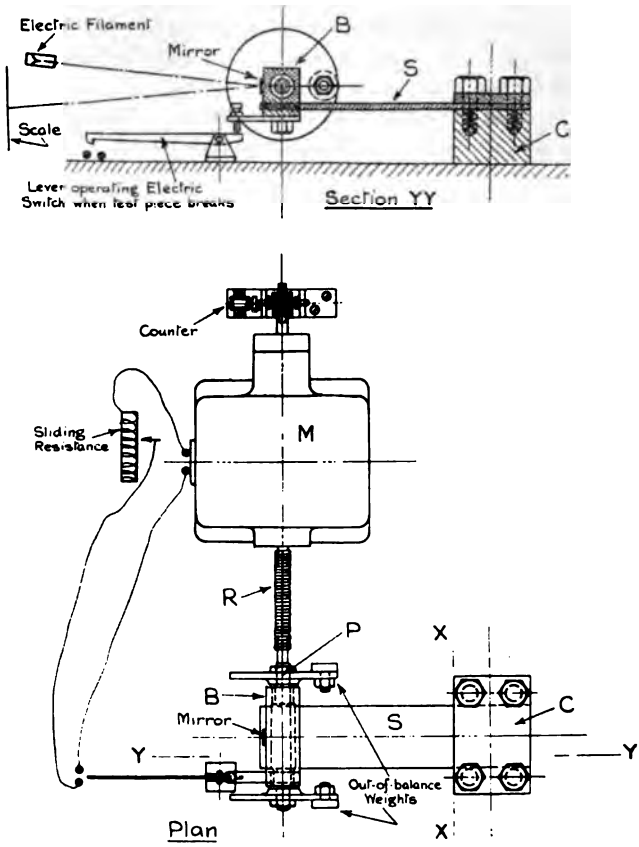

FIG. 170.—Vibration method of fatigue range determination.

characteristic of the particular mechanism used for their experiments ". Bairstow [6] says, " It may possibly be that the decreased range of stress found by Reynolds and Smith has some relation to the question of recovery, but further experiments are necessary to decide the question as the effect of the rigidity of the testing machine has not yet been fully investigated. In two

instances, at least, low ranges of stress have been traced to natural periods of vibration in the testing machine agreeing approximately with the period of repetition."

Eden, Rose and Cunningham[20] found no speed effect between 250 and 1300 revolutions per minute.

§ 152. **Effect of Rapid Changes of Section and Surface Condition on the Limiting Ranges of Stress.**—Stanton and Bairstow have shown that rapid changes of section have a marked effect on the resistance of materials to repeated direct stresses.

The standard test-piece that they used had a fillet of $\frac{3}{8}$ inch and for comparison with this they made experiments when (*a*) the fillet was reduced to 0·062 inch, (*b*) the specimen was screw-cut with a Whitworth V thread, and (*c*) the corners were left sharp.

TABLE LIII.

EFFECT OF RAPID CHANGES OF SECTION ON THE LIMITING RANGE OF STRESS.

Material.	Specimen Screw Cut with a V Thread. Percentage Reduction of the Limiting Range of Stress.	Specimen Having a Fillet 0·062 In. Radius. Percentage Reduction of the Limiting Range of Stress.	Specimen Left with Perfectly Sharp Corners. Percentage Reduction of the Limiting Range of Stress.
Swedish Bessemer steel, No. 3	31	32	52
Swedish Bessemer steel, No. 2	30	28	53
Swedish Bessemer steel, No. 1	33	32	52
Swedish charcoal iron	32	35	46
Piston-rod steel	33	29	40
Mild steel, No. 2	29	28	45
,, ,, ,, 1	26	28	36
Wrought iron, No. 1	23	19	40

The results are given in Table LIII and show :—

(1) That the resistance of all these forms are, in every case, far below the corresponding maximum limiting resistances of the materials.

(2) That the resistances of forms (*a*) and (*b*) are practically the same for any given material, and that the ratio of these resistances to the corresponding maximum limiting resistances does not vary greatly for the different materials.

(3) That in the case of the specimens having a sudden change of section the percentage reduction of the limiting range appears to depend on the hardness of the steel, being approximately

52 per cent. for the hard steels and 45 to 35 per cent. for the wrought irons and mild steels. It is, however, worthy of notice that even under the circumstances supposed to be most fatal to hard steels, i.e. a sudden change of section, these steels are very appreciably stronger than wrought irons and mild steels.

The results of some experiments, made by the authors using the Wöhler rotating cantilever method of test, are given in Table LIV. The standard test-piece, shown in Fig. 162, had a radius of 0·625 inch.

The percentage reduction in the range is seen to agree with the results obtained by Stanton and Bairstow.

TABLE LIV.

EFFECT OF RAPID CHANGES OF SECTION ON THE LIMITING RANGE OF STRESS (USING THE WÖHLER METHOD).

Material.	Ultimate Static Stress. Tons per Sq. In.	Limiting Range of Stress. Tons per Sq. In.			Maximum Reduction in Range. Per Cent.
		Fillet ⅛ In. Radius.	Fillet ½ In. Radius.	Sharp Corner.	
Nickel chrome shaft No. 1 . . .	61·9	57·0*	48·0	31·0	46
Nickel chrome shaft No. 2 . . .	45·2	46·0	—	29·4	36
Boiler plate . .	27·9	27·6	—	16·0	42
0·3 per cent. carbon steel . . .	37·5	33·4	—	17·0	49
0·4 per cent. carbon steel . . .	40·5	38·6	—	20·0	48
0·4 per cent. carbon steel . . .	40·8	34·6	—	18·0	48
0·4 per cent. carbon steel . . .	42·3	43·0	—	19·0	56

The injurious effect of scratches in parts of machinery subject to variations of stress is now recognised. Haigh says that cracks develop from surface scratches under stresses perceptibly lower than the normal. In some experiments, carried out by the authors, the alternate stress range of some aero crank shaft material was reduced from 56·0 (+ 28 to − 28) to 49·0 tons per square inch by a sharp scratch 0·003 inch deep.

Coker has also carried out some experiments, by his photo-elastic method, on the effect of scratches on the strength of materials (see § 100).

* 57·0 = +28·5 to −28·5.

There seems to be no doubt that many fatigue failures attributed to faulty material are really due to unsuitable fillets, sharp corners or surface scratches left during machining.

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CHAPTER XV.

RESISTANCE OF MATERIALS TO COMBINED STRESSES.

§ 153. FREQUENT cases of the combination of stresses are met with in engineering practice and the question of the resistance of materials to those stresses is now recognised as being of considerable importance.

Stress applications may be of three types:—

(1) Simple stress or stress in one direction.

(2) Biaxial stress or two stresses acting in directions at right angles to each other in the same plane.

(3) Triaxial stress or the application of three stresses at right angles to each other.

With simple stresses, direct tension or compression, the

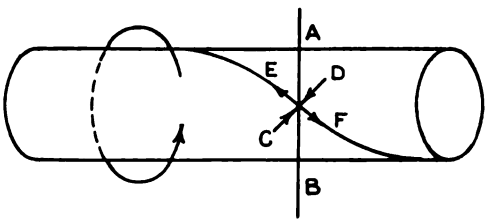

FIG. 171.—Shear as a case of combined stress.

practical constants (modulus of elasticity, elastic limit, yield stress, ultimate stress, Poisson's Ratio) are taken as a basis for design. With complex stress distribution the question arises as to the way in which these constants are to be used and several different theories have been expounded to account for the method of failure of materials under combinations of stresses.

The more important cases of compound stress, considered from an engineering standpoint, are biaxial.

Shear is an example of biaxial stress because it is equivalent to the combination of two equal principal stresses, one compression and the other tension, acting in directions at 45° with the shearing stress. Thus, in Fig. 171, the stress on the plane

AB, at right angles to the axis, is pure shear, the intensity of which depends upon the diameter of the bar and the torque applied. This shear is a combination of tension along the 45° plane CD and compression along the plane EF. It is well known that mild steel and wrought iron fracture, in a torsion test, across the plane AB, i.e. a shearing failure, while cast iron breaks along the plane EF, i.e. fails in tension, because it is stronger in shear than in tension.

Other combinations of biaxial stress are :—

(*a*) The crank shaft which is bent and twisted at the same time. This can be reduced to a case of tension combined with compression owing to the torque producing tension and compression on two planes at right angles as described above.

(*b*) The shell of a steam boiler, which has to resist circumferential and longitudinal stresses, is an example of the combination of two tensions.

(*c*) Plates, concrete slabs or floors supported round the edges and loaded in the centre are further examples of biaxial stress distribution.

Three-dimensional stress is found in thick steel cylinders under internal pressure accompanied by a longitudinal tension, also in concrete columns with spiral reinforcements and in hooped guns.

Investigators in the "combined stress" field of research have first of all to decide upon what they consider the point of failure of a material. The elastic theory, being based on Hooke's Law, is reliable up to the elastic limit (limit of proportionality or P limit) and therefore, considered mathematically, the elastic limit is the point of failure. This limit is dependent on the previous history of the material and is therefore variable and indefinite. For experimental purposes the yield point is used, in a good many instances, as the criterion of failure; this is no doubt due to the method of testing which does not allow the tests to be continued to the point of failure.

§ 154. **Theories of Failure Under Combined Stress.**—The most important theories advanced to account for the failure of materials under combined stresses are :—

(1) **Maximum Stress Theory (Rankine).**—This theory is that the material yields when one of the principal stresses reaches a certain amount (the stress determined by a simple tensile test). It assumes that a second stress, at right angles to the first, neither weakens nor strengthens the original stress.

(2) **Maximum Strain Theory (St. Venant).**—By this

theory failure is assumed to occur when the maximum strain reaches a value equal in magnitude to that at the yield point stress of the simple tension or compression experiment.

If a material is subjected to two or three stresses at right angles to each other, the maximum strain theory assumes that the strength is lowered if the stresses are opposite in sign and increased if they are of the same sign.

Thus if S_1, S_2 and S_3 are three stresses at right angles to each other and e_1, e_2 and e_3 are the unit strains in the direction of each of the respective stresses, also

E = the modulus of elasticity (assumed to be constant)
and $\frac{1}{m}$ = Poisson's Ratio.

Then
$$Ee_1 = S_1 - \tfrac{1}{m}(S_2 + S_3)$$
$$Ee_2 = S_2 - \tfrac{1}{m}(S_3 + S_1)$$
$$Ee_3 = S_3 - \tfrac{1}{m}(S_1 + S_2).$$

For simple tension S_2 and S_3 may be taken as zero and

$$Ee_1 = S_1, \text{ i.e. } E = \frac{S_1}{e_1} = \frac{\text{stress}}{\text{strain}}$$

which is the expression of the modulus of elasticity.

The maximum strain theory is mathematically correct if it is assumed:—

(*a*) To hold within the elastic limit.
(*b*) That Hooke's Law is absolutely correct.
(*c*) That the material is isotropic.
(*d*) That the effect of temperature is negligible.

By taking the yield point as the criterion of failure the variation of "E" between the limit of proportionality and the yield point is assumed to be without effect on the results.

(3) **Maximum Shear Theory.**—This theory assumes that the condition for initial yielding of a uniform ductile material corresponds to the existence of a specific shearing stress, the intermediate principal stress being without effect.

This theory as originally proposed, by Coulomb in 1776, refers to rupture of the material. It is adopted in Guest's [1] well-known work (1900) where it is used in conjunction with the yield stress. It is approximately verified by W. Scoble [2] and W. Mason.[3]

We can assume that simple tension is a case of combined triaxial stresses where two of the principal stresses are zero. Applying Guest's Law the bar must fail in shear and in this case

the maximum shear occurs in a plane at 45° and the shear stress intensity is 50 per cent. of the tensile unit stress. Seely and Putnam [4] find that the correct ratio of elastic shearing strength to the elastic tensile strength is 0·55 to 0·65 and therefore state that Guest's Law, which assumes the value to be 0·5, is not a correct statement of the law of elastic breakdown. Becker [5] found this ratio to be 0·56 and the authors [6] obtained a ratio of 0·63 to 0·68 for steels with ultimate strengths of 23 and 30 tons per square inch respectively.

Becker [5] as the result of experimental work proposes two laws of strength under combined stress, viz. :—

(1) That the strength at the yield point follows the MAXIMUM STRAIN THEORY until the shearing stress reaches the value of the shearing yield point.

(2) After this point, failure occurs according to the MAXIMUM SHEAR THEORY.

This suggestion appears to fit in very well with experimental work.

The maximum shear stress theory has been modified by Perry to include a frictional term proportional to the stress and perpendicular to the plane of shear. He noticed that brittle materials fracture at angles greater than 45° with the cross section and assumes that this is due to internal friction.

If θ = the angle found experimentally, μ (the coefficient of friction) = $\tan \phi$, then $\theta = 45^\circ + \frac{\phi}{2}$ for tension and $\theta = 45^\circ - \frac{\phi}{2}$ for compression.

For cast iron the angle (θ) is found to be 54¾°, which gives a value of μ of 0·35.

If $\phi = \theta$ this theory is the same as the maximum shear theory and Perry suggests that this is the case for wrought iron and mild steel.

(4) **The Maximum Resilience Theory.**—Haigh [7] proposes that the elastic limit of a material under complex stress is reached when the energy per unit volume attains a certain definite value. He bases this view on thermodynamic considerations and also finds that, when considered from the experimental aspect, the results fit in with this theory better than they do with either the maximum stress, maximum strain, or maximum shear theories.

Mallock [8] considers the volume extension limit or the limit of shear as the fundamental limits of a material and assumes that the material will fail when either is reached.

§ 155. **Experiments on Combined Stress.**—Most experimental work has been carried out on ductile materials. Only a few experiments have been made with brittle materials and further research in this direction is needed.

Tests on thin tubes in combined tension and torsion have been carried out by Guest,[1] Hancock,[9] Turner,[10] Mason [3] and Becker.[5]

Hancock and Turner used the limit of proportionality as the point of breakdown, Guest and Mason took the yield point while Becker adopted the "apparent" elastic limit. This is a point midway between the limit of proportionality and the yield point where the slope of the tangent to the stress-strain curve is 50 per cent. greater than it is at the origin. Seely and Putnam [4] also used the "apparent" elastic limit in their experiments.

Guest, Turner, and Becker added internal fluid pressure in order to obtain an additional stress.

Solid round specimens under tension or compression and torsion have been used by Hancock, Scoble,[2] and Smith [11] while the strength of thick cylinders under internal pressure has been determined by Turner,[10] Cook and Robertson,[12] and Bridgeman.[13]

Crawford [14] used flat steel plates clamped at the edges and subjected to fluid pressure on one side.

§ 156. **Repeated Applications of Combined Stresses.**—With repeated stress tests, the limiting range of stress in fatigue is a value that can be definitely taken as the one at which the material fails.

Although Wöhler made tests under repeated tension and repeated torsion, his results are difficult to compare owing to lack of specific information regarding the material used in the tests.

Alternating Torsion.—Both Turner and Stromeyer [15] have experimented with alternating torsion, the former found that the more ductile materials approximated to the maximum shear stress law while the more brittle samples were more nearly in agreement with the maximum strain theory.

Stromeyer's [15] work on alternating torsion is carried out in the machine shown in Fig. 172. S is the central crankshaft with a heavy flywheel F. It is driven by a direct-coupled electric motor (not shown). The throw, or double radius of each crank is 1 inch. Two connecting rods (KK) join the rotating cranks (CC) to the balanced rocking arms (GG) whose radii are 4 inches. The shafts of the rocking arms end in chucks (QQ), and the spindles of the two oscillating masses (WW) have similar chucks into which the ends of the test-pieces (TT) can be secured.

The oscillating masses (WW) are built up of a number of circular discs, whose polar moments of inertia are known. Forced torsional vibrations are given to the test-pieces (TT) by means of the rocking arms (GG) and oscillating masses (WW). The specimen acts as an elastic constraint between the rocking arm and the oscillating masses. The usual method of finding the limiting

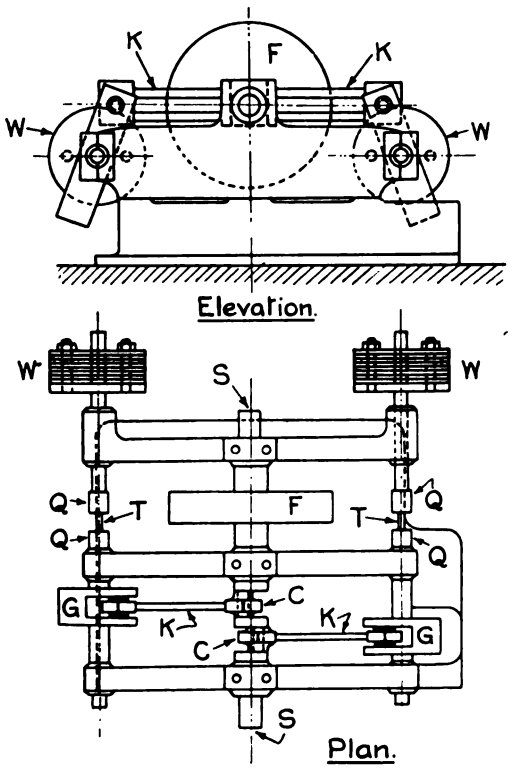

FIG. 172.—The Stromeyer machine for alternating torsion.

range of stress, by endurance tests, requires six specimens and, with the machine running continuously, occupies a week.

This machine was presented by Stromeyer to the National Physical Laboratory where it has been fitted up with improved lubricating arrangements and a device for preventing fluctuations of speed, due to variations of the current supply to the driving motor, has been added.

The regulating device (Fig. 173) consists of a small centrifugal water pump (A) driven by the Stromeyer machine and connected to a long vertical glass tube (B) which serves as a speed indicator. A branch tube (C) terminates in a U tube (D) containing mercury. The free surface of the mercury thus rises and falls with the speed of the machine. By means of two contacts, the mercury surface is made to open and close the primary circuit of a relay of the electric bell type. The tongue (E) of the relay opens and closes a circuit shunting the armature (F) of the motor. By this means, the "hunting" effect of the mer-

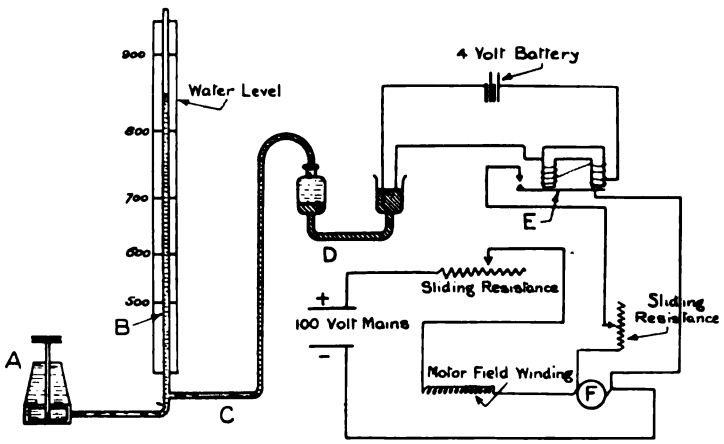

FIG. 173.—Speed regulating device for Stromeyer machine.

cury surface can be limited to about $\frac{1}{32}$ inch, giving the required speed with a variation of about ± 0·3 per cent.

The method adopted at the N.P.L. for calculating the stress in the specimen under test is as follows: The motion of the oscillating mass (W, Fig. 172) is determined by causing a reed, carrying a pen at its extremity, to vibrate in synchronism with a tuning fork of known frequency. A very stiff specimen is placed in the machine and run at a fixed speed. The vibrating reed is then drawn across a card attached to the oscillating mass. A series of dots which are obtained give a time-displacement curve for the mass. This curve is found to be an extremely close approximation to simple harmonic motion.

If f_s = the maximum shear stress in the specimen
θ = amplitude of the mass in radians
M = polar moment of inertia of the mass (W)
I = second polar moment of section of the specimen
n = the speed of the machine
C = a constant

then, assuming a straight line stress distribution,

$$f_s = \pm \mathrm{CM}\theta n^2.$$

Using the Stromeyer machine and a hollow specimen (Fig. 174) endurance tests on a normalised carbon steel of 53 tons per square inch ultimate stress give a limiting range of alternating stress in shear of ± 10·5 tons per square inch while Wöhler tests on the same material give a limiting range of bending stress of

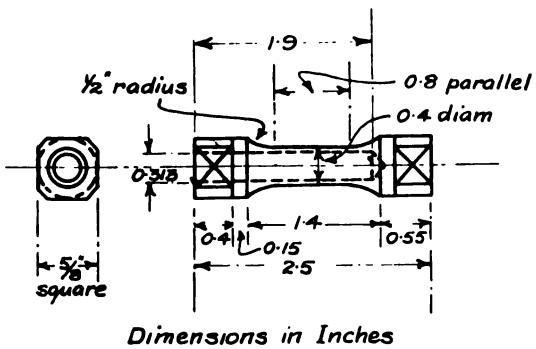

FIG. 174.—Alternating torsion test-piece.

± 21·0 tons per square inch. This material therefore fulfils Guest's Law (§ 154 (3)). Results have been obtained on heat-treated steel for which this theory does not hold and it is possible that the problem may be connected with the structure of the material.

A torsional fatigue machine embodying the inertia method has been constructed by D. J. McAdam.[16]

Some experiments were carried out by Stanton and Batson[17] in 1916 on combined torsion and bending. A diagrammatic sketch of the arrangement which was adopted is given in Fig. 175. In the position shown, the cross section of the specimen at S is subject to a twisting moment WD where D equals the distance of the weight W from the axis of the test-piece XX, and to a bending moment Wd. When the head had turned

through 180° the moments were equal in amount but opposite in sign. When the head had turned through 90° from the position shown the maximum stress was that due to a bending moment WD plus that due to the direct loading, but as in all cases this stress was below the known fatigue limit of the material under reversals of simple bending, its effect was taken to be negligible, and the specimen was assumed to be subject to reversals of the combination of bending and twisting alone.

Experiments on alternating bending combined with torsion have been made by Prof. Akimasa Ono.[18] The machine used is of the Sondericker type (see § 147) the test-piece being subject to uniform bending moment and rotated continuously. The

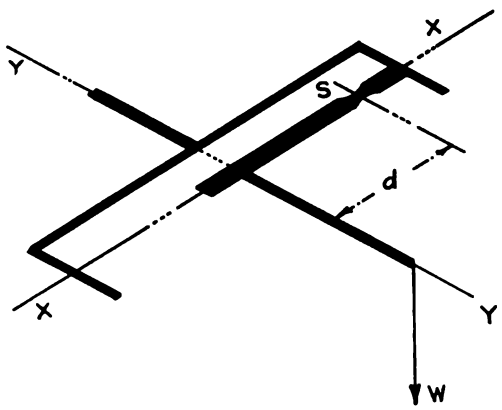

FIG. 175.—Method of repeated applications of combined stress.

specimen (T, Fig. 176) is supported by two ball-bearings (BB) in a casing (C), which rests in its position and carries the load by means of knife edges (KK) arranged in an exactly similar manner on the front and back sides of the casing The test-piece, fitted to the holders, is under a uniform moment = WL where L is the distance between the knife edges which in this machine is 20 centimetres, and W is the load on each of the knife edges (KK).

A steady shearing stress is simultaneously induced in the specimen by connecting the testing machine with an electric absorption dynamometer which consists of a small direct current dynamo placed on an iron frame suspended by ball-bearings. The torque is measured by means of a weight placed on a scale

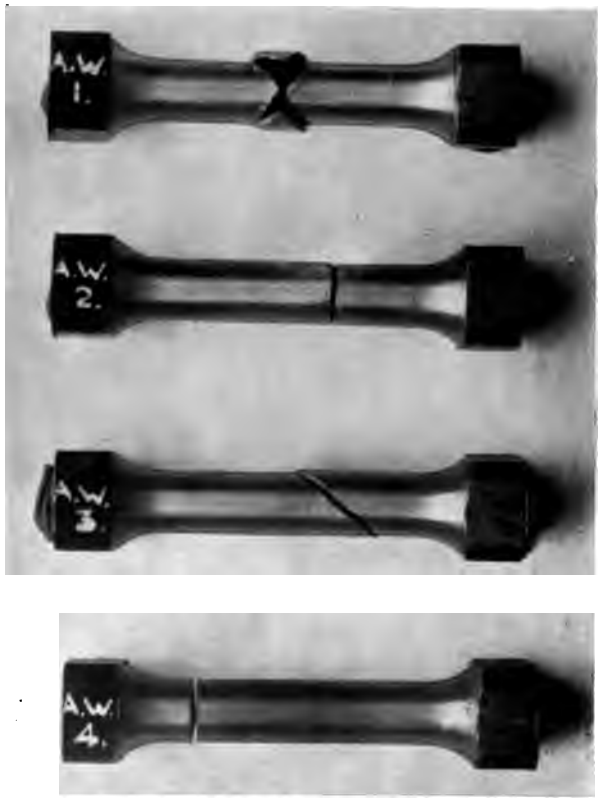

FIG. 177.—Alternating torsion fractures.

[*To face p.* 251.

pan hung from a knife edge at a distance of 30 centimetres from the axis of the shaft.

§ 157. **Forms of Alternating Torsion Fractures.**—Cast iron or brittle steel (such as the 53 tons per square inch steel referred to in § 156) usually fracture along a 45° helix whereas the fracture of ductile material is plane and at right angles to the axis of the bar. Some experiments carried out by Stanton and Gough at the National Physical Laboratory, confirm a theory propounded by R. V. Southwell that flaws in a ductile material under torsion intensify the maximum tension in the material and cause spiral fractures at 45° to the axis.

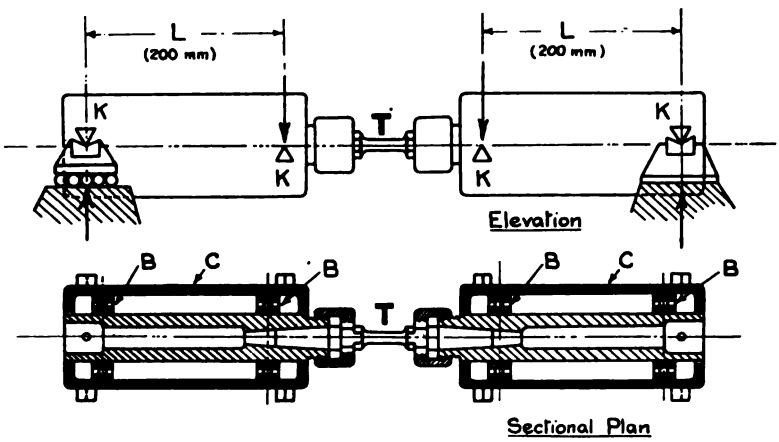

FIG. 176.—Ono's fatigue machine.

Four hollow test-pieces (see Fig. 174) were prepared from a bar of mild steel and were broken in alternating torsion. The fractures are given in Fig. 177.

Specimens AW/2 and AW/4 were untreated and show the fractures usual with ductile materials. Specimen AW/1 had a hole (0·012 inch diameter) drilled through it to act as an artificial flaw. The fracture started at the hole and proceeded along lines at 45° with the axis as shown. The fracture of specimen AW/3 (also at 45°) started at a point where there was a pronounced tool mark on the internal surface.

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CHAPTER XVI.

RAPID METHODS OF DETERMINING THE LIMITING RANGES OF STRESS (FATIGUE RANGES) OF MATERIALS UNDER REVERSALS OF SHEAR STRESS OR REVERSALS OF TENSILE STRESS.

§ 158. SEVERAL methods of investigation have been suggested, the most important being :—

(i) Determination of the rate of increase of the width of the hysteresis loop with stress.

(ii) Detection and measurement of the progressive failure of steel by means of change in the magnetic permeability.

(iii) Determination of the rate of increase of temperature with stress.

(iv) Measurement of the rate of increase of strain with stress.

§ 159. A modification of his optical load extension recorder (see § 130) has been designed by Prof. Dalby [1] and constructed by J. Buckton & Co., Ltd., Leeds, by means of which the load-elastic extension curve of a material is automatically recorded to an enlarged scale. The load can be applied to a definite amount, gradually removed and then reapplied, forming on the diagram an elastic hysteresis loop. Such loops can be repeated on the same diagram. Dalby has found that the rate of increase of area of the loops decreases as the stretching proceeds and that the loop area tends to a limiting value. There is insufficient data so far available to say definitely whether the information obtained in this way gives values which agree with the fatigue ranges obtained from endurance tests.

§ 160. A considerable amount of work is being carried out by C. W. Burrows [2] on the magnetic analysis of steel. Burrows is of opinion that " magnetic tests at different time intervals will indicate structural change in steel long before actual failure occurs ". Magnetic testing of steel under alternating stresses may prove an index of its fatigue strength.

§ 161. **Calorimetric Method.**—This method has been used by Stromeyer,[3] who determines the torsional fatigue limit by

measuring the stress at which a small but perceptible rise of temperature of the specimen takes place due to internal work. By means of a special holder, water is passed slowly along the specimen, its temperature being measured at inlet and outlet. The torsional fatigue limit is assumed to occur at the stress corresponding to a rise of temperature of the outlet water of 0·02° C., which is the limit of accuracy of the mercury thermometer employed.

The calorimetric method has recently been used at the National Physical Laboratory [4] and the results obtained there are in good agreement with those found by other methods. The temperature is, however, measured with much greater accuracy than is possible by the Stromeyer method. With tests of this character it is necessary to employ very sensitive methods of

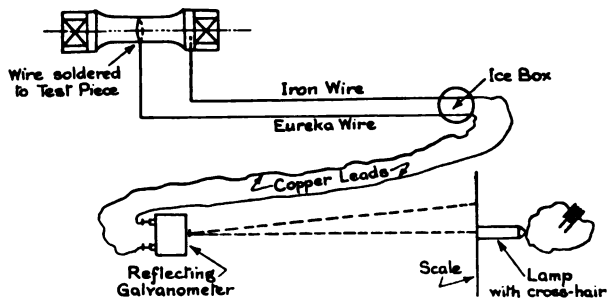

FIG. 178.—National Physical Laboratory calorimetric method of fatigue range determination.

measurement in order to detect the first departure from a straight line law. For this reason it is probable that all Stromeyer's values, obtained by the method described above, are on the high side.

In the National Physical Laboratory method an iron eureka thermocouple is employed, one wire is tightly wrapped round the centre of the specimen and soldered. A hole is drilled in one enlarged end of the specimen and the second wire soldered in. The thermocouple wires are joined in an ice-box (a thermos flask is convenient to use for this purpose) to two copper leads and are connected to a delicate dead beat reflecting galvanometer, the image of a cross hair and spot of light being focussed on a graduated ground glass scale. The arrangement is shown diagrammatically in Fig. 178. An example of a curve obtained by this method is given in Fig. 179.

§ 162. **Strain Measuring Methods.**—(i) *J. H. Smith's*[5] *Arrangement.*—Smith has developed a strain method for which he uses the machine described in § 148 (page 234) and illustrated in Fig. 166. An optical extensometer (Fig. 166), of the Martens mirror type but using only one rhomb, is attached to the specimen throughout the test. The image of a small orifice, which is illuminated by an arc lamp (L) is focussed on a screen (X) by means of the concave extensometer mirror. A plane mirror (m_1) is fixed on a light shaft (w) and is operated by the lever r and cam e attached to the shaft driving the unbalanced flywheel. For strain-stress diagrams the spot of light is made to reflect

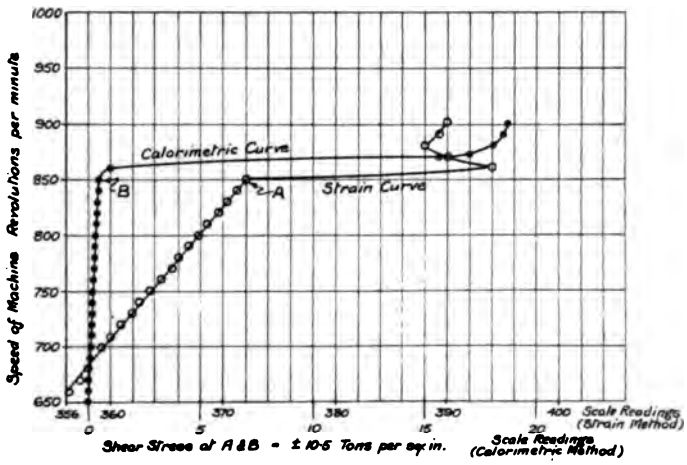

FIG. 179.—Curves for rapid determination of the limiting range of alternating shear stress.

from mirror m_1 on to a second screen (X_1). The strain of the test-piece gives a vertical motion to the spot of light while the oscillation of the mirror m_1 produces the horizontal motion.

The method of test consists in applying a definite range of direct stress on the specimen by the unbalanced flywheels, and and then adding tensile load by means of the spring. This addition of tensile load (or mean stress) increases both the minimum and the maximum stress in the test-piece while the range remains constant. Thus, if the unbalanced flywheel applies stress alternating from − 14·2 to + 14·2 (range 28·4) and a tensile (or mean stress) of 4·4 is added by the spring, then the maximum stress is increased to + 18·6 and the minimum stress becomes

$-14{\cdot}2 + 4{\cdot}4 = -9{\cdot}8$, the range remaining 28·4 (i.e. 18·6 + 9·8) as before.

It is found that, by gradually adding mean stress to the fixed range of stress, a small but definite yield (which may be as small as 0·0002 inch) is ultimately observed at a stress which is in close agreement with the fatigue limit corresponding to the stress distribution obtained from endurance tests. It should be noted that the fatigue ranges obtained correspond to repeated stresses (from a definite minimum to a definite maximum) and not alternating stress ranges as are obtained by the "Wöhler" test. Results on a 3·25 per cent. nickel steel are given in Table LII, § 142,

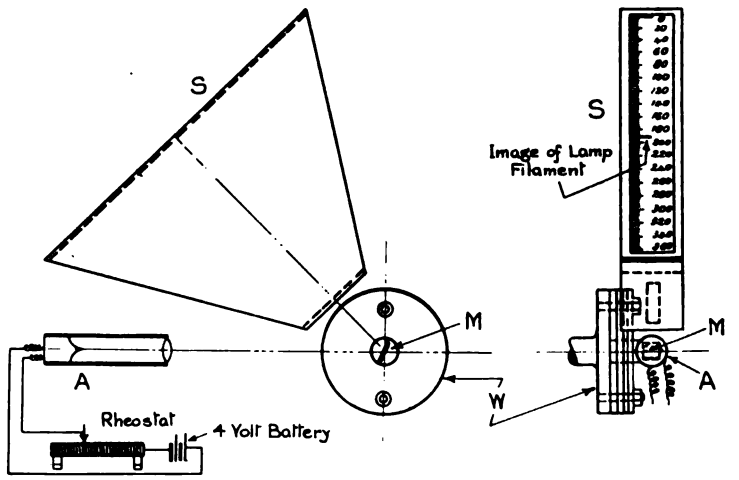

FIG. 180.—Addition to Stromeyer machine for rapid determination of fatigue ranges.

and plotted in Fig. 155. It will be seen that the results obtained by the endurance method and rapid "yield-range" method are in very good agreement. Results on a complete series of steels are given in the paper by J. H. Smith.

(ii) *National Physical Laboratory Method.*—A strain method of determining fatigue ranges in alternating torsion and alternating bending has been developed by H. Gough of the Engineering Department of the National Physical Laboratory.[4]

(*a*) *Alternating Torsion Method.*—The improved Stromeyer machine (§ 156) is used for the tests with the addition of a simple optical arrangement (see Fig. 180). A plane mirror (M) is fitted to the end of the shaft of the oscillating mass (W). The image

of a single filament lamp (A) is focussed, after reflection at the mirror, on to a graduated ground glass scale (S) contained in a cardboard box. As the mass oscillates, the image moves up and down the scale. The machine is usually run at speeds which vary from 350 to 1000 r.p.m. At these speeds, owing to the persistence of vision, the image appears as a band of light with well-defined edges. The total amplitude varies from 220 to 400 mm. and the scale can be read in daylight to 0·5 mm. This amplitude does not represent the actual strain of the specimen under test, but the strain together with the movement of the rocking arm. This point, however, is immaterial as only the rate of increase of strain is required.

The specimen is placed in the holders and the machine run at a low speed. The strain scale readings are taken at this speed and at increments of 10 r.p.m. as the speed is increased. At a certain speed depending on the material, the amplitude of the motion of the spot suddenly increases and this increase is sudden and definite.

The ranges calculated from "yields" are found to agree with those from endurance tests. The curve (Fig. 179) shows a typical result obtained by this method together with the record from a calorimetric test on the same material. It will be seen that the "yield" strain curve gives the more definite indication. A feature peculiar to the machine employed for these tests is that any slight yielding of the material is increased exceedingly rapidly. This is due to the fact that the small yielding slightly increases the amount of oscillation of the disc which applies the torque—thus increasing the torque at the same speed and causing further yielding and in its turn increased oscillation. The amount of yield is therefore rapidly multiplied and gives a very definite indication of the point of failure.

TABLE LV.

Material.	Torsional Fatigue Limit—Shear Stress. Tons/Sq. In. A.	Fatigue Limit Under Reversed Bending Stresses. Tons/Sq. In. B.	Ratio A/B.
Boiler plate 0·25 per cent. carbon	± 7·00	± 12·4	0·56
0·27 per cent. carbon steel .	± 7·32	± 15·2	0·48
0·30 „ „ „ . .	± 8·76	± 16·7	0·52
0·42 „ „ „ . .	± 8·66	± 17·3	0·50
0·65 „ „ „ . .	± 10·50	± 21·0	0·50
Pure nickel (rolled bar) . .	± 6·58	± 13·0	0·51
Light alloy „ „	± 4·58	± 10·2	0·45

The results of some torsional "yield" range limits are given in Table LV, together with Wöhler endurance test results on the same materials. It is seen that the torsional ranges are approximately half of the Wöhler ranges and therefore obey Guest's Law (§ 154 (3)).

(*b*) *Reversals of Bending Stress.*—The well-known N.P.L. type of "Wöhler" machine (shown in Fig. 161) has been adapted for these tests. Instead of dead weight loading a lever testing machine (A) is used for the purpose, as shown in Fig. 181. The load can in this way be increased, by moving the travelling jockey (B), without introducing sudden steps. A plain mirror (C) is fixed to the end of the specimen, its plane

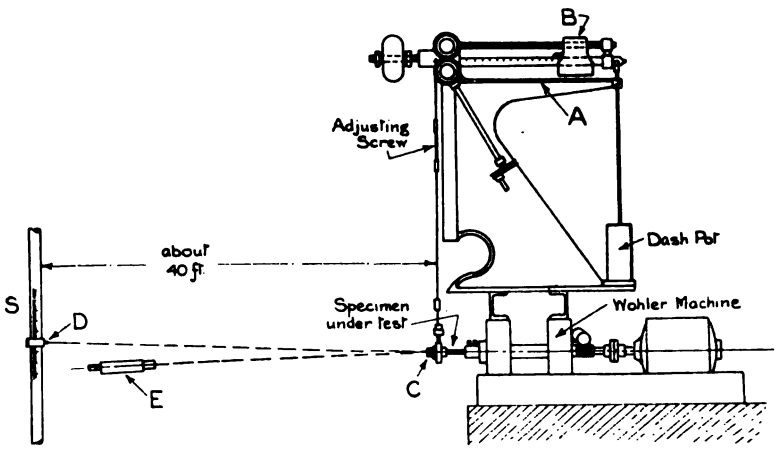

FIG. 181.—Method of determining the limiting range of stress under reversed bending stresses by the strain or yield range.

being perpendicular to the axis of the specimen. The image of a filament (D), after reflection by the mirror, is focussed by a telescope (E). The filament is attached to a holder which can be moved along a scale (S) until it coincides with the cross-wire of the telescope. The method consists of determining the change of slope of the end of the specimen with increase of load or stress. Fig. 182 gives the form of mirror holder found most convenient. It is fitted on to the test-piece by means of the split screwed end (F) and carries at its opposite end the mirror (G) which is dovetailed into it. There are two slots (H and J) at right angles to each other, these allow the screws (K and L) to adjust the position of the mirror relatively to the axis of the test-piece. The

arrangement enables the plane of the mirror to be rapidly and accurately set at right angles to the axis of the specimen.

Fig. 183 gives the plotted results for a 53 tons per square

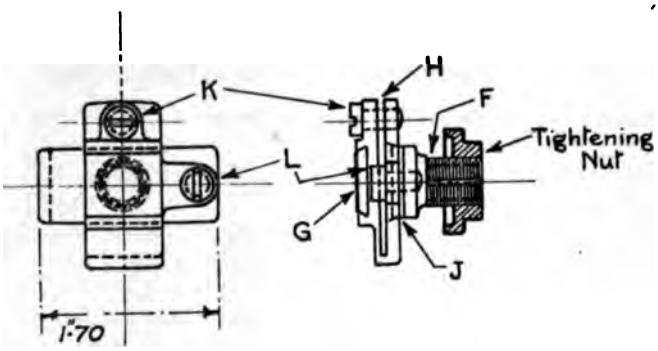

FIG. 182.—Mirror holder for Wöhler test-pieces.

inch steel—the same bar of material for which the torsional curves are given in Fig. 179.

The time taken to determine the fatigue limit of one speci-

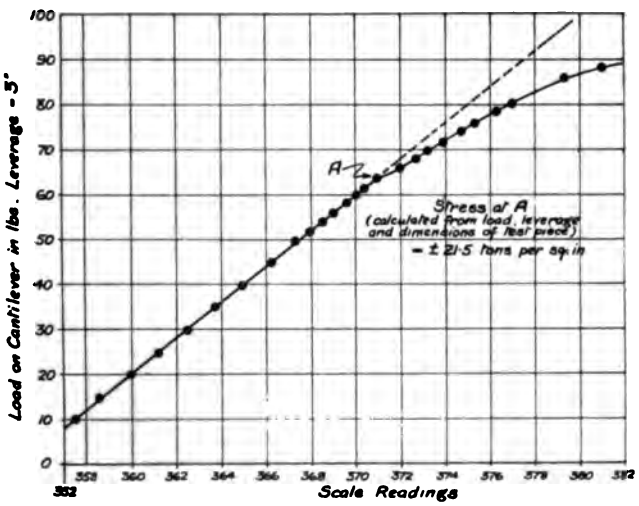

FIG. 183.—Curve for strain method of determining the limiting range of stress under reversed bending stresses.

men in either torsion or bending by the above methods varies from five to fifteen minutes, depending upon the number of observations taken.

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CHAPTER XVII.

ALTERNATING BENDING TESTS BEYOND THE YIELD POINT.

§ 163. THE principal objection to the commercial adoption of repeated stress tests is the time and expense of conducting tests in which millions of applications of stress are required in order to obtain the result.

Many machines have been designed in which the test-piece is broken rapidly under alternating stresses which exceed the yield point. Such tests do not give information as to relative "fatigue" strength of materials but have been found useful as indicating mechanical defects, incorrect heat treatment, and brittleness.

§ 164. **Arnold Testing Machine.**[1]—In this test, in its latest form, a test-piece $\frac{3}{8}$ inch diameter and 5 to 6 inches long is firmly fixed, at one end in a vertical position, in the vice of the machine. It is bent backward and forward, through a distance of $\frac{3}{8}$ inch on either side of the vertical at a height of 3 inches above the face of the dies, by a slotted steel head fixed to the reciprocating part of the machine. The length of slot is larger than the diameter of the test-piece (usually $\frac{3}{4}$ inch with a stroke of the machine of $1\frac{1}{8}$ inch) so that an impact or shock is introduced at each alternation of stress. The standard speed adopted is 650 alternations per minute. The number of alternations to fracture is recorded. Arnold and other investigators improvised shaping or slotting machines to perform the test.

It should be noted that, in his earlier work, Arnold[2] used a test-piece $\frac{3}{8}$ inch SQUARE with the force applied 4 inches above the line of maximum stress. The deflection was $\frac{1}{2}$ inch or $\frac{1}{16}$ inch on either side of the vertical and the number of alternations was 168 to 266 per minute.

§ 165. **Landgraf-Turner Alternating Impact Machine.**—This machine is especially designed and constructed to carry out the Arnold test in order to standardise the conditions employed. In place of the straight line movement of the shaping

machine a rocker arm is substituted (Fig. 184) to economise space and, by reason of its radius being equal to the free length of the test-piece, maintain a constant leverage during the whole stroke.

The number of alternations are recorded by a veeder counter which stops registering when the test-piece breaks. The test-piece is $\frac{3}{8}$ inch diameter but, with this machine, the distance from the top of the vice to the striking point of the hammer is 4 inches instead of 3 inches as used by Arnold in his latest experiments.

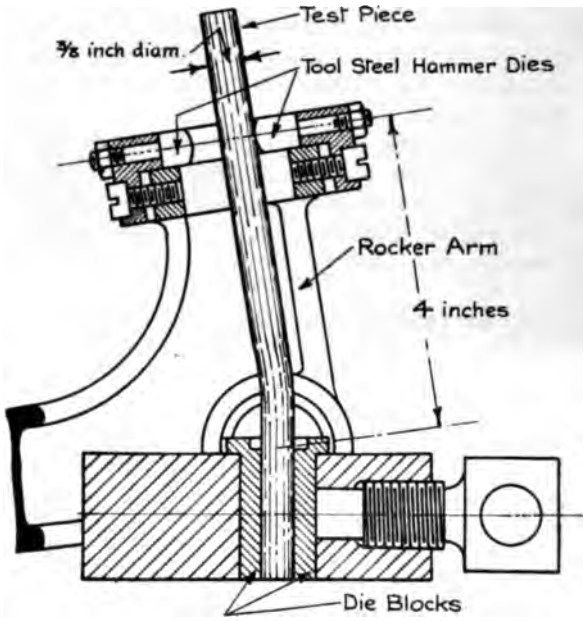

FIG. 184.—The Landgraf-Turner alternating impact machine.

This machine is manufactured in the U.S.A. by Queen & Co., Philadelphia.

J. B. Kommers[3] of the University of Wisconsin has carried out an investigation with a Landgraf-Turner machine. He summarises his results as follows:—

(1) A very important factor in a repeated stress test similar to that performed by the Landgraf-Turner machine is the amount of deflection which the specimen receives. When the deflections are less than 0·30 inch the change in the number of cycles re-

quired for rupture is very great even for small changes in the amount of deflection.

(2) Impact applied to the specimen has PRACTICALLY NO EFFECT upon the number of cycles required for rupture.

(3) At speeds of about 700 cycles per minute the number of cycles for rupture is slightly less than at speeds of about 150, but for small changes of speed this effect is practically negligible. When the deflection is small the results on the same material do not seem to be as uniform as when the deflection is about 0·30 inch or more.

(4) The condition of the surface of the specimen has an important effect upon the number of cycles required for rupture.

§ 166. **Sankey Hand Bending Test.**[1]—The principle on which the test is based is to bend backwards and forwards a test-piece $\frac{3}{8}$ inch diameter and 4 inches long through a fixed angle until failure. The number of bends and energy required for each bend being recorded. The test is carried out on a machine, manufactured by C. F. Casella & Co., Ltd., and shown diagrammatically in Fig. 185. A flat steel spring (B) has one end gripped in a vice (A) which forms part of the bedplate, and the other secured to a holder (C) in which the test-piece (D) is fixed. The test-piece is also held in a handle (E), 3 feet long, by which it is bent backwards and forwards through an angle of $91\frac{1}{2}°$, located by the indicators (F and F).

The energy required to bend the test-piece is measured by the deflection of the spring (B) which is recorded on the paper attached to the drum (G). The horizontal motion of the pencil (H) is actuated by the holder (C) through wires (M and N) and a multiplying pulley. The wire, in the earlier machines, is kept taut by a spring contained in the box O, but this is now replaced by a weight hanging from the wire M, which then passes over a vertical pulley. The motion of the pencil is proportional to the energy required to bend the test-piece. The diagram is calibrated by noting the length which corresponds to a measured pull at a known leverage from the point of bending of the test-piece. This is easily carried out by inserting the lever the other way in and attaching a spring balance to the groove at the end of the lever. The point of application of the pull is at such a distance that pulls of 10, 20, 30 lbs. correspond to bending efforts of 30, 60, 90 lbs.-ft. The movement of the pencil holder (H) moves the drum through one tooth of a ratchet wheel (K) which is attached to it so that a diagram is drawn such as is shown in the illustration.

The practical value of the Sankey test is stated by Hatfield,[5] who carried out an extensive series with it, to be as follows :—

"The energy absorbed in breaking the Sankey test-piece is practically proportional to the product of the average bending

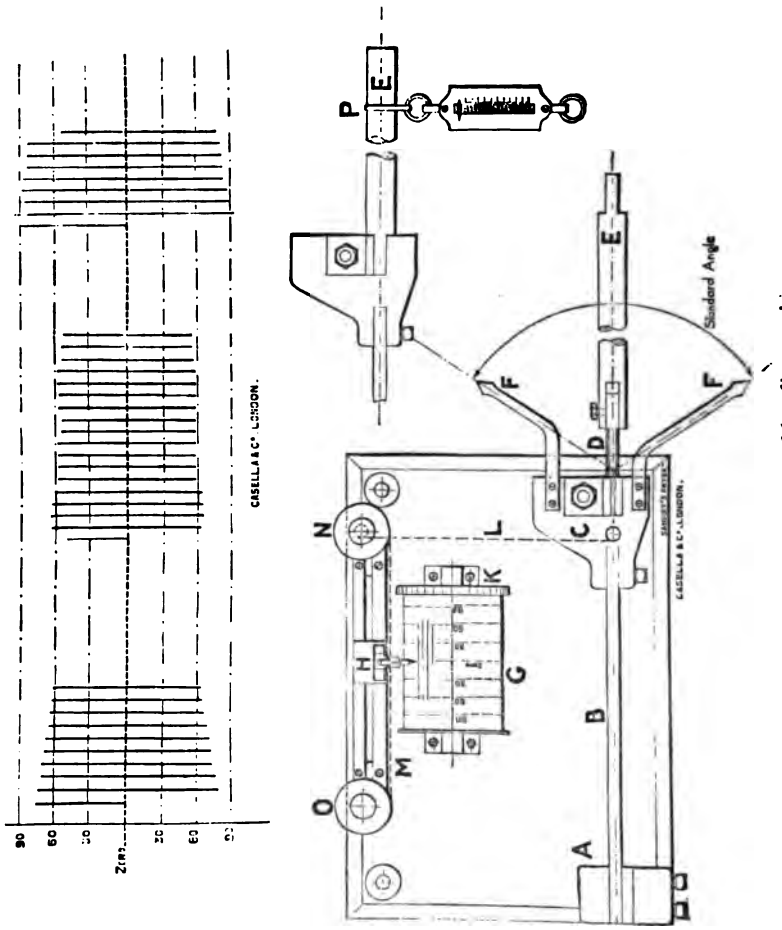

FIG. 185.—Sankey hand bending machine.

moment and the number of bends withstood. These two items may be compared roughly to the maximum stress and reduction of area in the tensile test, i.e. for conditions of increasing hardness in general, the maximum bending moment increases and the number of bends decreases. It is necessary that we should

point out that in a number of instances we have obtained high absorptions of energy with high tensile.

"The maximum bending moment in the Sankey test follows the maximum stress in tension fairly closely, so that the latter values can be predicted within a few tons per square inch from the Sankey values. The variation found in the values of the number of bends in the Sankey are rather wider and of a less predictable nature. In this respect the Sankey test discriminates and emphasises a certain quality of the material in a manner not similarly brought out in other tests, except perhaps to some extent in the Arnold test. From a knowledge of the quality of the steel, its analysis, etc., experience has shown that fairly definite values of ductility in the tensile test, as measured possibly by the reduction of area, can be expected in conjunction with given values of tensile strength if the steel is free from defects. Similarly the number of bends in the Sankey test should reach such values which with experience of the test may also be fairly definitely established. There are, however, several outstanding exceptions. It certainly appears that samples which gave Sankey values well below what has been predicted from an average good steel of the same tensile strength, were in nearly all cases also somewhat inferior in reduction of area."

The diameter of the Sankey test-piece is $\frac{3}{8}$ inch and its free length $1\frac{3}{4}$ inch. Owing to the fact that the machine, as supplied, is not suitable for steels of higher tensile strength than 50 to 60 tons per square inch, Hatfield suggests a test-piece 0·3 inch diameter and free length $1\frac{3}{4}$ inch for these steels.

Sankey[6] gives the following constants for inferring static test results from those obtained on his hand bending machine:—

$$\text{Yield point (tons per sq. in.)} = \frac{\text{initial bending effort in lbs.-ft.}}{C}$$

where C = 2·1 for steels up to 0·3 per cent. carbon
and 2·7 for medium carbon steel.

$$\text{Breaking strength (tons per sq. in.)} = \frac{\text{max. bending effort in lbs.-ft.}}{1{\cdot}54}$$

$$\text{Elongation (on gauge length} = 4\sqrt{A}) \times \text{reduction of area} = \frac{\text{number of bends}}{1{\cdot}9}.$$

§ 167. **The Upton Lewis[7] Toughness Testing Machine,** manufactured by Tinius Olsen Testing Machine Co., is very

similar in principle to the Sankey machine. It is, however, operated by a motor (M) or belt drive giving 250 alternations per minute instead of by hand, and the method of measuring and recording the energy absorbed is slightly different. Referring to Fig. 186, where the machine is shown, the test-piece (T) is bent backwards and forwards by an arm operated from the adjustable crank (B). The energy is measured by the amount of the compression of the springs (CC) which is recorded by the bell-crank indicator (D) marking on a continuous recording paper.

§ 168. **Other Investigators and Machines.**—Boudouard[8] used a machine in which one end of the specimen was clamped in a vice and the free end vibrated. The vibrations were maintained electro-magnetically and the oscillations were recorded optically and photographically.

Schuchart[9] tested wire under repeated bending. The wire was gripped in curved faced jaws and bent backwards and forwards into contact with the curved faces.

Huntingdon[10] applied alternate bending by means of an attachment to a shaping machine.

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[2] Arnold, "Inst. Civ. Eng. Proc." (Supplement), 1903, and "Engineer," Sept. 2nd, 1904, p. 227.
[3] Kommers, "Repeated Stress Testing," "Int. Assoc. Test. Mat. Proc.," 1912, Vol. II, Pt. II, paper V4a.
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[5] Hatfield and Duncan, "N.E. Coast Inst. of Eng. and Shipbuilders Proc.," March 19th, 1920.
[6] Sankey, Blount and Kirkaldy, "Inst. Mech. Eng. Proc.," May, 1910.
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[9] Schuchart, "Stahl und Eisen," July 1st, 1908.
[10] Huntingdon, "Inst. of Metals Jour.," 1915.

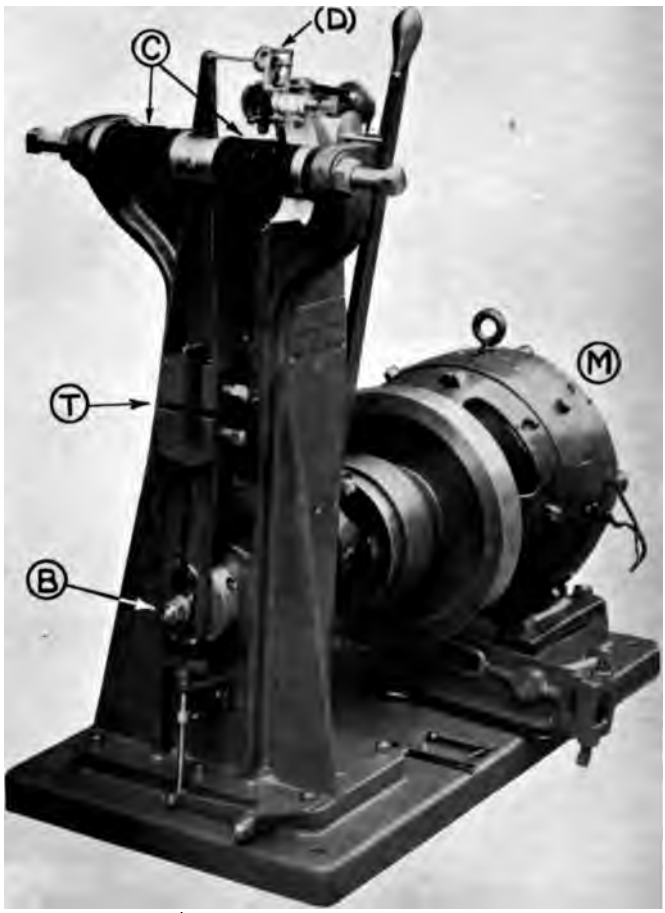

Fig. 186.— Upton Lewis testing machine.

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CHAPTER XVIII.

HARDNESS AND ABRASION TESTS.

§ 169. AN examination of the methods employed in hardness testing shows that each of them falls into one or other of two distinct categories. These are:—

(1) Indentation tests, in which the surface of the material under test is permanently distorted by the pressure of a hard steel ball, cone, or knife edge.

(2) Abrasion or scratch tests, in which particles of the material whose "Hardness" is to be determined are torn away from its surface by sliding contact with some other substance, whose corresponding resistance is so high that its surface remains unimpaired by the action.

If each of these methods were a measure of the same definite property of the material which is as characteristic of it as, say, its elasticity, it is evident that the ratio of the results of any two of the methods would be the same for every material tested. Comparisons between the results of these various tests have formed the subject of several researches which have been published during recent years. The general conclusions as summarised by Turner[1] appear to be that, although an approximate agreement may seem to exist between the various methods when applied to the case of relatively pure metals in their cast or normal state, yet when the resistance to deformation is due to tempering or to mechanical treatment no comparison is possible.

That this should be so would seem to follow from the consideration that the resistance which any so-called hardness is supposed to measure is that which the body under test exerts against a complex distribution of stress over its surface which has partially deformed or disintegrated it, and it is evident that its value will depend, not on the stress constants of the material such as its yield point, ultimate tensile and shear stresses, but on intermediate stresses, the precise nature and distribution of which are unknown and whose ratio to the stress constants may not be

the same for the same method. If, therefore, such resistance, without qualification, be defined as the hardness of the material in its broadest sense, it is clear that hardness is no more a definite quality of a material than is the strength of a piece of steel of definite dimensions. In the latter case, if the nature, amount and distribution of the stress are known, its resistance has a definite value which can be calculated. The only difference between this case and that of the hardness test is that, since in the determination of hardness there is no possibility of estimating the stress magnitude and distribution, we are driven more to direct observation of the consequences of such distribution than to a calculation of these consequences from the known characteristics of the material. Mechanical phenomena of this kind are familiar to engineers under other aspects, such as in the case of the resistance of ships and aircraft to propulsion; but whereas in these latter cases the problem is to determine the resultant force exerted by the unknown pressure distribution, in the present case, as in the corresponding one of the resistance of materials to impact, the unknown quality is the ultimate resistance of the material to the unknown stress distribution. In all the cases, however, the practical method of solution is an experimental one, and consists of setting up a similar, or nearly similar, state of stress on a specimen of the material whose behaviour is under investigation and noting its effects.

H. Le Chatelier[2] says, "the problem therefore seems to be to establish two or three methods of reference for hardness, giving as widely different results as possible, so that hardness (which is an essentially complex phenomenon) may be studied under all its phases. Afterwards, for each particular application the reference method which is most applicable to the conditions may be used."

That this view is now being accepted is indicated by the development, in recent years, of what are called wear tests. For example, there are wear tests for measuring the particular form of disintegration which takes place on the surface of steel rails due to the rolling abrasion of heavily loaded wheels. The characteristics of this kind of wear are the extremely small amount of the relative movement between rail and wheel and the high intensity of the compressive stress at the line of contact. On the other hand, there are wear tests of lubricated surfaces in which the pressure is relatively small and the rate of slipping large and the same conditions of wear occur, without lubrication, with pins and gauges.

§ 170. **Indentation Tests.**—The indentation method of determining hardness has been applied in three ways:—

(1) By testing the material with itself.

(2) By pressing (statically) a harder material into the material under test.

(3) By producing the indentation by dropping a ball or cone-pointed hammer on to the material and measuring the rebound of the hammer or size of the indentation.

§ 171. **The Material Tested with Itself.**—Reaumur [3] in 1722 shaped right-angled prisms from two materials which were to be compared and pressed them together. The axes of the prisms were at 90° and the right-angled edges came into contact, forming a cross, the relative hardness was measured by the depths of the indentations.

A. Foeppl [4] used two cylindrical test-pieces of the material whose hardness was required. They were placed one on the other, with their axes at right angles and were pressed together in a testing machine. Foeppl used the pressure per unit of flattened surface as a measure of the hardness, because he found that the surface of indentation was proportional to the pressure applied.

Haigh [5] has recently re-introduced the test with the substitution of square for cylindrical or triangular prisms. He gives the hardness number as $= \frac{L}{R^2}$

where L = the load
and R = the length of the damaged edge of the prism.

Reaumur, Foeppl, and Haigh's methods are shown diagrammatically in Fig. 187.

The necessity for the use of two test-pieces as well as the fact that the test cannot be applied to a finished article are probably the reasons why this method of test is not commonly used. There is, however, no limit to the hardness of the material which can be tested, as the test is independent of the use of a harder material as an indenting tool.

§ 172. **The Material Tested with an Indenting Tool (Statically).**—Many different kinds of indenting tool have been tried and many ways have been suggested to express the relative indenting hardness.

Calvert and Johnson,[6] and Kirsch,[7] determined the load required to produce a permanent indentation of a given depth but, whereas Calvert and Johnson used a truncated cone and a depth

of 3·5 mm., Kirsch employed a cylindrical plunger of 5 mm. diameter and a depth of 0·01 mm.

The test adopted in 1856 by the United States Ordnance Department [8] was a determination of the volume of the indentation produced by a pyramidal point under a load of 10,000 lbs. A volume of 0·5 cubic inch was taken as unit hardness.

Middleberg [9] used an indenting tool in the form of a curved knife edge, for studying the hardness of tyres. The knife edge was $\frac{3}{4}$ inch long, had an angle of 30° and was formed with an edge curved to 1 inch radius. The reciprocal of the length of the indentation under a load of 6000 lbs. was taken as a measure of the hardness.

Unwin [10] also employed a knife edge, but in his case it was

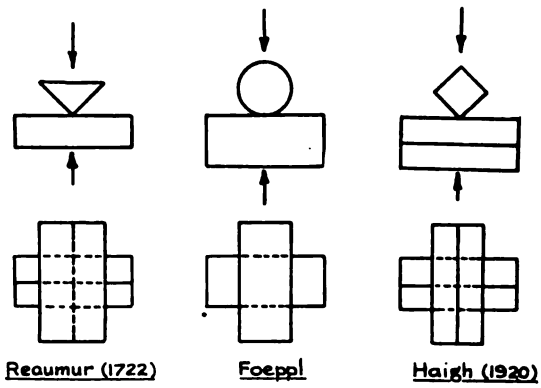

FIG. 187.—Hardness testing.

straight and consisted of a piece of hardened and ground $\frac{3}{8}$ inch square steel $1\frac{1}{2}$ inch in length. Each tool thus had four indenting edges having angles of 90°. The material tested was formed into test bars $\frac{1}{2} \times \frac{1}{2} \times 2\frac{1}{2}$ inches and the knife edge was placed on the bar at right angles to its length, overlapping it by $\frac{1}{2}$ inch on each side. The hardness number was taken as P/H where P = the load in tons and

H = the depth of the indentation in inches.

§ 173. **Brinell Hardness Test.**—Hertz [11] in 1882 defined hardness as the strength of a body relative to the kind of deformation which corresponds to contact with a circular surface of pressure. He further stated that the hardness of a body is to be measured by the normal pressure per unit area which must act at the centre of a circular surface of pressure in order that in

some point of the body the stress may just reach the limit consistent with perfect elasticity.

Hertz confined his experiments to glass and similar brittle materials and showed that it was impossible to apply his method of measurement to metals.

The method of test devised by J. A. Brinell [12] in 1900 is now extensively employed. A hardened steel ball is pressed under a known load into the material to be tested and the Hardness Number is taken as the stress per unit of spherical area. The reason why Brinell used the spherical area is not clear as there does not appear to be any advantage gained by using it instead of the projected area $\left(\frac{\pi d^2}{4}\right)$.

If P = pressure in kilograms
D = diameter of the ball used in millimetres (see Fig. 188)

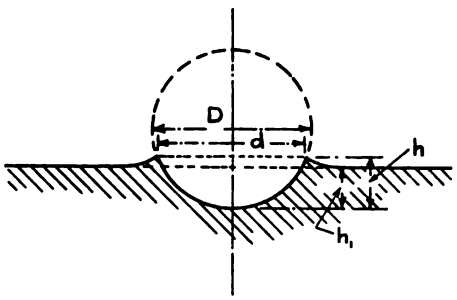

FIG. 188.—Diagram of Brinell ball impression.

d = diameter of the indentation in millimetres
h = the depth of indentation in millimetres

then $h = \frac{1}{2}(D - \sqrt{D^2 - d^2})$ mm.

and the spherical area of indentation

$$A = \pi Dh = 1{\cdot}571\ D(D - \sqrt{D^2 - d^2}) \text{ sq. mm.}$$

The Brinell Hardness Number = H = P/A.

The diameter (d) is usually measured by a micrometer microscope. By the use of some forms of Brinell instruments the depth (h_1) of the indentation is taken as the test proceeds (§ 185). With these instruments the depth which is measured is h_1 and not h (see Fig. 188). It should be noted that, owing to the rising of the edges of the Brinell indentation, h_1 is not equal to h and, as the amount of this side extrusion is not the same with different materials [13] under similar conditions,

the ratio of h_1/h is not always constant. It therefore follows that the hardness number obtained in this way is not the hardness number as defined by Brinell.

It is found that the hardness number varies with the diameter of the ball and pressure employed. For strictly comparable results fixed values must be used for D and P. The values standardised by Brinell are :—

D = 10 millimetres.
P = 3000 kilograms, except for soft material when a value of 500 kilograms may be used.

Devries[14] has shown that a linear relation exists between load and depth of indentation (h_1) for all pressures from zero to 3000 kilograms.

§ 174. **Variation of Brinell Hardness with Pressure and Diameter of Ball.**—C. Benedick[15] of Upsala showed that within the range of his tests the value of $\frac{P(\sqrt[5]{D})}{A}$ was nearly constant and that with a ball of diameter = D_1 and load of 3000 kilograms Brinell's Hardness Number = $\frac{P}{A}\left(\sqrt[5]{\frac{D_1}{10}}\right)$.

In order to allow for variation of pressure, H. Le Chatelier[16] proposed the further modification

$$H = \frac{P_1}{A_1} \times \sqrt[5]{\frac{D_1}{10}} \times \frac{20000}{17000 + P_1}$$

where H = BRINELL Hardness Number.
P_1 = load employed in kilograms.
A_1 = spherical area of the indentation (calculated from the diameter) in square millimetres.
D_1 = diameter of the ball used.

Both the equations suggested by Benedick and Le Chatelier are empirical and only give approximate values.

E. Meyer[17] in some published results in 1908 showed (1) that $P = ad^n$ where "n" is a constant depending on the material and "a" is a constant for a given material and given ball diameter. (2) That the mean pressure per unit area ($4P/\pi d^2$) is constant for a given angle of indentation whatever the diameter of the ball.

It follows from Meyer's law of comparison that, as d/D and $P/\frac{1}{4}\pi d^2$ are constant for similar indentations on the same material, P/D^2 is also constant where

P = pressure, d = diameter of impression and
D = diameter of the ball.

This relationship is useful where the piece of material is so small that a pressure of 3000 kilograms cannot be applied with a 10-millimetre ball. It is then only necessary to use a smaller ball and a load determined by the above relationship to obtain the standard hardness number required; thus if a ball 5 millimetres diameter ($= D_1$) is used the load to be applied is

$$= \frac{P \times D_1^2}{D^2} = \frac{3000 \times 5^2}{10^2} = 750 \text{ kilograms.}$$

Some results obtained by Baker[17A] and given in Table LVI show remarkably good agreement of the hardness numbers obtained in this way.

TABLE LVI.

COMPARISON OF BRINELL HARDNESS NUMBERS WHEN USING BALLS OF DIFFERENT DIAMETERS.

Steel.	Diameter of Ball in Mm.	Diameter of Impression in Mm.	Load in Kg.	Brinell No.
A	10	6·3	3000	85
	7	4·4	1470	85
	5	3·13	750	87
	1·19	0·748	42·5	86
B	10	4·75	3000	159
	7	3·33	1470	158
	5	2·35	750	163
	1·19	0·567	42·5	158
C	10	3·48	3000	306
	7	2·43	1470	308
	5	1·75	750	310
	1·19	0·411	42·5	311

§ 175. **Size of Test-piece, and Effect of Time on the Results and the Applications of the Brinell Hardness Test.**—H. Moore found that (1) the depth of the indentation in a Brinell test should not be greater than 1/7 of the thickness of the test-piece. (2) The centre of the indentation should not be less than 2½ times its diameter from the edge of the test-piece.

The time during which the pressure is applied is important. It is found that the time effect is most marked up to about 10 seconds application of the load but after about 10 seconds the

effect is very small. Consequently it is usual in specifications to draft the Brinell Hardness Test clause as follows:—

"The Brinell Hardness Test, where specified, shall be made with a 10-millimetre diameter ball and a load of 3000 kilograms WHICH SHALL BE MAINTAINED FOR NOT LESS THAN 15 SECONDS. Prior to testing, the skin of the sample shall be removed by filing, proper grinding or machining at the point to be tested."

Among the most important applications of the Brinell test are the following:—

(1) For rapid control of chemical carbon determinations during iron and steel smelting.

(2) For testing finished articles without damaging the same, such as rails, tyres, armour plates, gun-barrels of all kinds, structural steel, etc.

(3) For examining the nature of the material in entire or broken parts of machinery where the making of a tensile test-bar is impossible

(4) For testing the degree of hardness and softness obtainable by the thermal treatment of any steel.

(5) For testing uniformity of temper.

(6) For ascertaining the effect of the nature and temperature of various hardening fluids.

(7) For studying the effect of cold working.

It has been shown by numerous observers (Ast, Breuil, Brinell, Charpy, Dillner, Le Chatelier, etc.) that there is a close relationship between the Brinell Hardness Number and the ultimate tensile strength of a material.

Dillner[19] finds that, in the case of steel, tensile strength in tons per square inch = C × Brinell Hardness Number. The values of "C" are given in Table LVII.

TABLE LVII.

Brinell Hardness Number.	Value of "C". Ball Pressure Normal to the Direction of Rolling.	Value of "C". Ball Pressure in the Direction of Rolling.
Below 175 . .	0·230	0·225
Above 175 . .	0·219	0·206

Unwin[20] deduced the following constants from a table compiled by Hadfield:—

$$T = 0{\cdot}2H + 6$$
$$Y = 0{\cdot}23H - 13{\cdot}5$$

where H is the Brinell number (in kilograms per square millimetres)

T = ultimate tensile strength in tons per square inch
Y = yield stress in tons per square inch.

Values of the Brinell Hardness Number, obtained under standard conditions, of various steels together with the ultimate strength are given in Table LVIII.

TABLE LVIII.

BRINELL HARDNESS NUMBERS OF STEEL.

Particulars of Steel.				Heat Treatment.	Ultimate Stress. Tons per Sq. In.	Brinell Hardness Number.
	Carbon. Per Cent.	Nickel. Per Cent.	Chro-mium. Per Cent.			
Carbon steels . .						
,, . .	·12			N. at 900° C.	29	128
,, . .	·19			As rolled	26	120
,, (boiler plate)	·25			,,	29	128
,, . .	·26			N. at 900° C.	35½	159
,, . .	·32			As rolled	37	158
,, . .	·42			,,	41	172
,, (rail steel) .	·45			,,	44	183
,, . .	·45			N. at 870° C.	44	192
,, . .	·65			As rolled	53	236
Nickel steels . .	·15	2·6		N. at 880° C.	32	143
,, ,, . .	·17	2·9		N. at 860° C.	32	140
,, ,, . .	·17	6·0		,,	42	187
,, ,, . .	·37	3·6		,,	44	196
Nickel chrome steels	·17	3·0	0·45	N. at 820° C.	36	163
,, ,, ,,	·28	1·5	0·80	N. at 850° C.	40	174
,, ,, ,,	·31	3·3	0·82	N. at 820° C.	76	341
,, ,, ,,	·27	3·45	0·95	A.H. at 850° C.	72	321
,, ,, ,,	·32	3·7	1·42	,,	115	477

N. stands for Normalised. A.H. means Air Hardened.

§ 176. **Brinell Hardness Testing Machines.**—The Brinell Hardness Test is quite conveniently carried out in any machine in which a pressure of 3000 kilograms can be accurately applied, such as a universal testing machine having a compression attachment, by the use of a special tool for holding the ball.

Special machines have, however, been developed for the purpose and these are of two main types.

(1) In which the load is applied by oil pressure and measured by a pressure gauge or dead weight control.

(2) Dead weight or lever machines.

§ 177. **Oil Pressure Machine.**—An example of the first type of machine is shown in Fig. 189. This is the apparatus supplied by J. W. Jackman & Co., Ltd., Caxton House, Westminster, of the Aktiebolaget Alpha (Sweden) design.

The ball (K) is attached to the downwardly acting ram of an hydraulic press. The test-piece is placed on the adjustable table (S) and is raised into contact with the ball by the hand-wheel (*r*). The pressure is produced by a small hand-pump and may be read directly in kilograms on a pressure gauge. The machine is also provided with a dead weight control consisting of a piston, accurately fitted without packing, carrying a cross bar (*i*), small cylinder (*a*) and weights (*p*). The small cylinder is connected to the top of the press so that the intensity of pressure is the same on the piston as on the ram. The maximum pressure is regulated by the weights (*p*), and when this pressure is reached the piston rises in the cylinder. The pressure remains constant as long as the piston "floats," forming a small hydraulic accumulator.

The small piston is formed by a steel ball and the piston rod has a cup-shaped end which presses on the ball. Any leakage of oil past the piston is collected in a receptacle (*d*), from which it is returned to the reservoir through the funnel (*t*).

The pressure is released by opening a valve (*v*) which connects the top of the pressure chamber with the reservoir.

§ 178. **Herbert's Power-operated Brinell Machine.**—The leading features of this machine are:—

(i) The load is automatically applied by a cam which is power operated.

(ii) There is a modified lever arrangement for weighing the load.

(iii) The time taken to apply, maintain and remove the load is controlled and uniform for all tests.

The machine is shown in Fig. 190. The test-piece is placed on an anvil (A) and raised into contact with the ball (B) by means of a hand-wheel and screw (H).

Application of the Load.—The screw (H) is held axially in a vertically moving cylindrical ram (R) which, when forced upwards, applies the pressure. It is regulated and resisted by the weighing element. The ram (R) is operated by a cam (C) and roller (*r*), the latter being attached to the bottom of the ram.

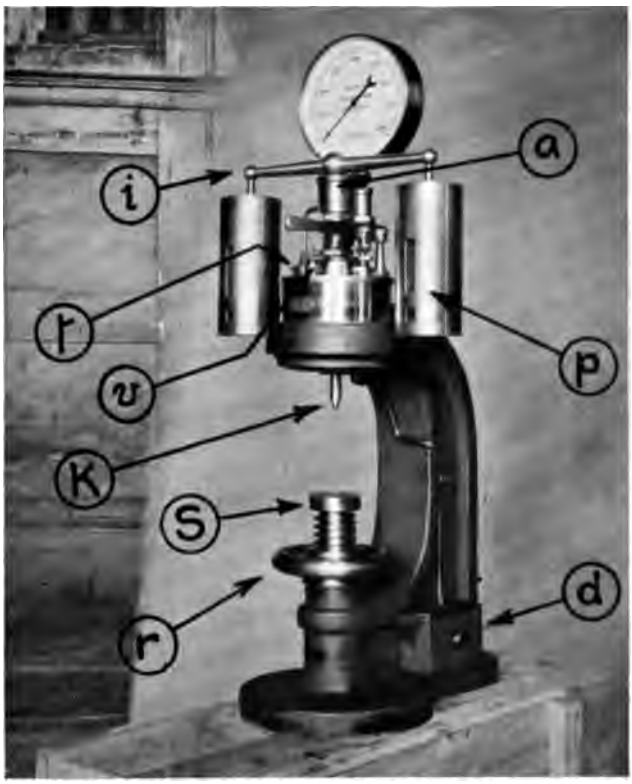

FIG. 189.—Oil pressure Brinell hardness machine.

[*To face p.* 276.

he cam is designed so that one revolution applies the load adually, leaves it on for a definite period and then releases it. he cam is driven through worm-gearing (G) from a shaft (S) hich rotates at a constant speed. The worm is clutched to the

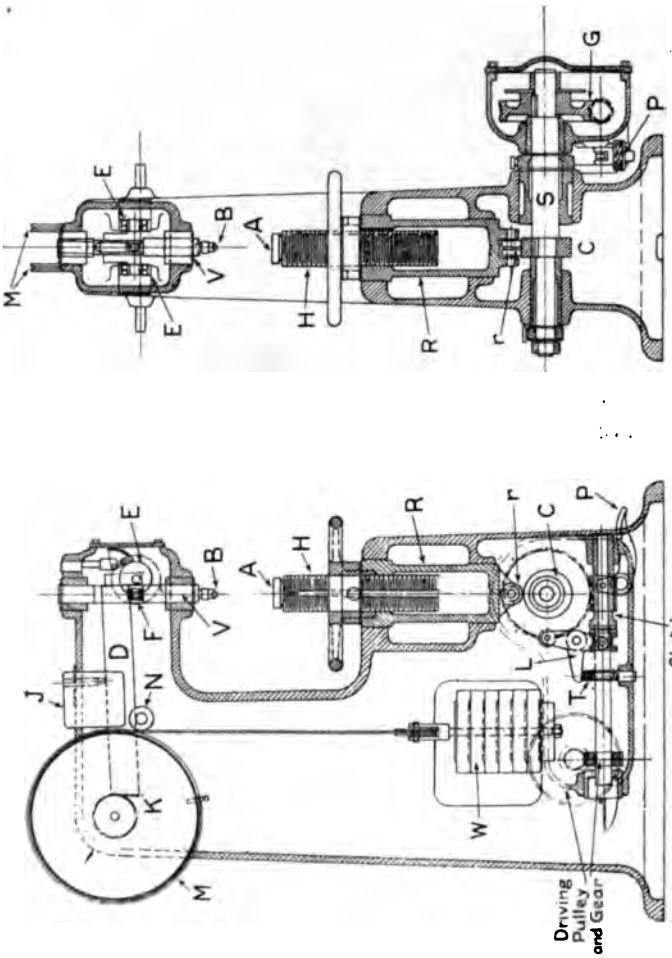

Fig. 190.—Herbert power-operated Brinell machine.

aft, a spring (T) being arranged to open the clutch and also t on a bell-crank lever (L) which carries a roller to engage a tch in a disc on the cam shaft. Thus when the pedal (P), own in the front of the machine, is depressed the roller is leased from the disc and the clutch is thrown in, whereupon

the cam makes a complete revolution before the drive is automatic:lly released by the re-entry of the roller into the notch.

Weighing Arrangement.—The 10 mm. ball (B) is carried by a vertical plunger (V) whose weight is balanced by a spring. When the ram (R) is forced upwards, the plunger operates a lever (D) whose fulcrum is a pair of ball-bearings (E), and the point of application of the pressure is a hard steel roller (F) between two hard steel seatings. The other end of the lever is provided wi h teeth meshing in gears (K) which are keyed to pulleys (M) carrying the large weights (W) by means of a wire cable. Six loose weights (W) are provided giving the standard pressures of 3000 and 500 kilograms. The lever (D) is provided with a sliding weight (J) for initially adjusting the machine for each load and a stop (N) for limiting its downward movement.

The machine is made by Alfred Herbert, Ltd., Coventry.

§ 179. **Avery's Dead Weight Brinell Machine.**—This machine is shown in Fig. 191. The specimen is placed on the weighing platen (*s*), and if of any considerable size its weight is "tared off" by moving one of the sliding poises (*c*) upon the weighing steelyards until the weighing system is balanced. The ball (*k*) is then brought into contact with the test-piece by lowering the screw by which the pressure is applied. This is done quickly by unscrewing the thumb-screw (A) at the top of the standard and revolving the screw by the small hand-wheel (*d*) which is keyed to it. The thumb-screw is then screwed up tightly, to secure the locking plate (*f*) and prevent the rotation of the screw. The pressure is then applied, by means of a worm and worm-wheel in a casing (*h*) operated by the large hand-wheel (*g*) at the side of the machine. The weights (*p*) are "set" for the prescribed load and the lifting of the steelyards indicates that this load is applied.

The system of levers for measuring the pressure is that adopted by W. & T. Avery & Co., Ltd., Birmingham, in all their platform weighing machines and is found to be extremely sensitive to small differences of load.

The leverage of the machine can be obtained directly by measurement but it is also calibrated by dead weight loading on the platen (*s*).

§ 180. **The Johnson Hardness Testing Machine** (manufactured by Brown Bayleys Steel Works, Ltd., Sheffield).—This machine has been devised to ensure rapid and accurate working and at the same time withstand rough workshop use, require practically no attention or adjustment and be easily movable

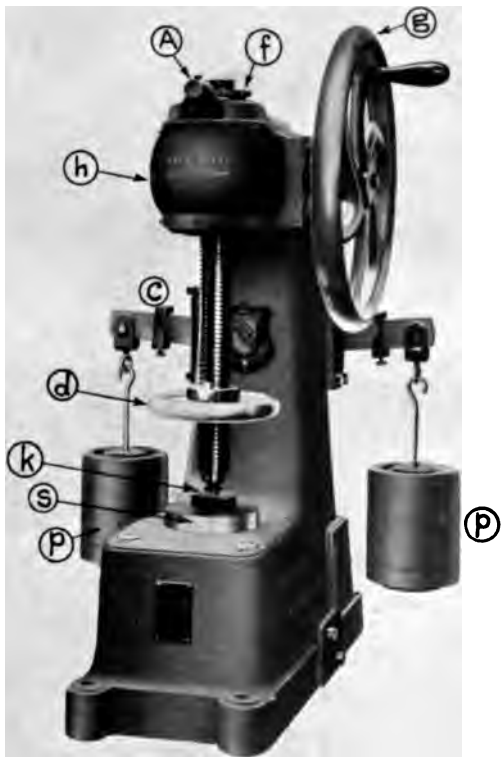

FIG. 191.—Avery's dead weight Brinell machine.
[*To face p.* 278.

from place to place without detriment. The total weight of the machine is only 100 lbs. and its overall dimensions are 28 × 22 × 9 inches. It will take test-pieces $4\frac{1}{2}$ inches thick and the indentation can be made at distances up to $3\frac{1}{2}$ inches from the edge.

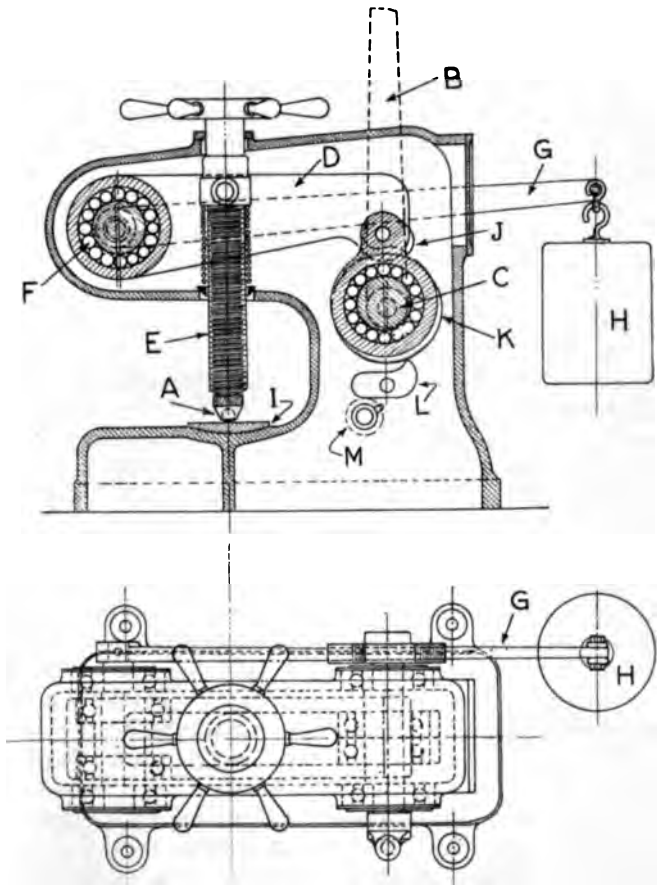

FIG. 192.—Johnson hardness testing machine.

Description of the Machine.—The arrangement of the machine is shown in Fig. 192.

Pressure is applied to the steel ball (A) by means of the lever (B) and ball-bearing eccentric (C) through the single lever (D) and screw (E). The other end of the lever (D) is held by an

eccentric in ball-bearings (F) to one of which is attached the lever (G) and weight (H). The weight (H) is raised by the eccentric (F) when the pressure on the ball (A) reaches 3000 kilograms and any further movement of the operating lever (B) tending to apply further pressure on the ball only results in raising the weight still more.

Method of Making Test.—The specimen to be tested (which must have a smooth *flat* surface) is placed on the table (I). The adjusting screw (E) is then brought down until the steel ball (A) rests on the prepared surface of the specimen. The lever (B) is then pulled forward until the weight (H) rises allowing the pawl (J) to fall into the toothed sector (K) which will automatically prevent any further movement of the lever (B). The load may be kept on for any desired length of time by means of the retaining pawl (L) which is moved in and out of position by means of the knurled handle (M). In order to release the pressure the lever (B) is replaced to its original vertical position and the adjusting screw (E) raised.

A similar machine of larger size is made by the same firm. This takes test-pieces 9 inches thick and weighs about 150 lbs.

§ 181. **Brinell Pliers.**—For ascertaining the Brinell hardness of small and thin specimens, such as cartridge cases, Rudge Whitworth, Ltd., have devised a hand instrument which they call Brinell Pliers. They are shown in Fig. 193 and consist essentially of a pair of pliers, one nose (A) of which serves as an anvil for supporting the cartridge case or specimen to be tested. The other nose (B) carrying a cylinder fitted with a piston, at the back of which is a spring. The end of the piston stem projects a short distance and carries a small hardened steel ball (C) $\frac{3}{64}$ inch diameter. A locking arrangement enables one to adjust the compression on the spring, the usual pressure being 22 lbs. To operate the instrument the specimen is placed between the anvil and the ball and the plier handles are grasped and the pressure applied. This brings the specimen into contact with the ball and forces the ball and piston back until the surface of the specimen comes into contact with the face through which the ball projects. Consequently, the actual pressure between the ball and the specimen is quite independent of the pressure exerted by hand. The diameter of the indentation is measured microscopically and the readings are quite definite, even on hardened spring steel.

The instrument found extensive use controlling the manufacture of small arms ammunition. It has been employed for

measuring the skin hardness of many varieties of hardened steel articles.

A somewhat similar arrangement of pliers has been designed, used and patented by W. H. Hatfield for a research into the hardness of stainless and other cutlery.

This instrument is also essentially a pair of nippers, one jaw of which contains the steel ball while the other holds an adjustable anvil. The principal feature of these nippers is the arrangement of a large leverage in addition to that provided by the pincers themselves. This is carried out by means of an auxiliary lever having a fulcrum on a "bridle" attached to one pincer arm and provided with a cam face bearing on a pin communicating with the other arm.

The load is not regulated by a helical spring behind the ball, as in the Rudge Whitworth pliers, but by a horse-shoe spring between the arms of the nippers. The deflection of the spring causes any excess pressure over a predetermined amount to be taken on a stop.

A steel ball 2·4 millimetres diameter is used with a load of 170 kilograms and this produces an impression which is measured by a microscope and is similar to the standard Brinell impression. The hardness number calculated as

$$\frac{\text{load}}{\text{spherical area of indentation}}$$

is therefore directly comparable with the standard Brinell results. The information obtained by W. H. Hatfield in this investigation has resulted in a considerable improvement in the hardness of stainless cutlery. The improvement is principally due to suitable heat treatment.

§ 182. **Small Machines for Testing the Brinell Hardness of Thin Sheet.**—(i) Goodale and Banks have developed a "baby" Brinell machine for testing thin sheet, using a ball $\frac{1}{16}$ inch in diameter and a load of 15 kilograms. They found that great care had to be exercised in the manner in which the load was applied. A dead weight of 15 kilograms was used and the diameter of the impression measured with a metallurgical microscope with a 16-millimetre objective and filar micrometer type of eye-piece. It is essential, for the measurement of small indentations, that there should be vertical illumination.

(ii) A large amount of work has been carried out at Woolwich since 1913 by H. Moore, on small hardness machines. A modified and improved machine based on Moore's experience is

supplied by Alfred Herbert, Ltd., who have acquired the rights of manufacture from the inventors.

With a machine of this type hardness of materials 0·01 inch in thickness may be determined. Such articles as thin-walled tubes and hollow forms may be tested without internal support; loaded small arm cartridge cases may be tested without removal of bullet or charge; cutlery blades, which would be disfigured by a large impression, even if the thickness of the article would permit of the ordinary test, may be tested by an impression so small as to be imperceptible to the unaided eye. The hardness of cutting tools can be determined close to the cutting edge and the hard skin of case-hardened work can be successfully tested.

Balls of 1 or 2 millimetres in diameter are used together with loads calculated to give indentations similar to those obtained by the standard Brinell method (see § 173). Conditions as to size of test-piece conform to requirements which are found necessary by experimental work (§ 175).

The machine (Fig. 194) consists of a base plate (B) which supports two threaded columns (C_1, C_2). The table (T_1) for the reception of the specimen to be tested is carried by these columns and is adjustable up and down by hand-wheel (H), so as to set the table at the required height. The base plate is furnished with levelling screws.

At the top of the columns the cross-head (K), in the centre of which is a fine pitch non-rotating screw (S), is mounted. This can be raised and lowered by a hand-wheel provided with a ball-thrust washer.

The lower end of the screw (S) carries a suspension stirrup which is prevented from rotating by arms bearing against the columns, and from this stirrup is hung a loading stirrup to the upper portion of which is attached the ball-holder (T_2), while the lower portion carries the weights (W).

The connection between the two stirrups consists of a spherical surface in the loading stirrup, bearing in a hole in the other, so that one hangs from the other. The friction of the spherical surface in its hole effectually damps out any pendulum action.

In use a suitable size of ball and ball-holder are selected according to the character of the material to be tested. The ball is attached to the ball-holder by india-rubber solution, so as to render the changing of balls an easy matter. The table is set at the required height and the work is then placed in position under the ball, a supporting block or fixture being used if desired.

FIG. 193.—Rudge Whitworth's Brinell pliers.
[*See p.* 280.

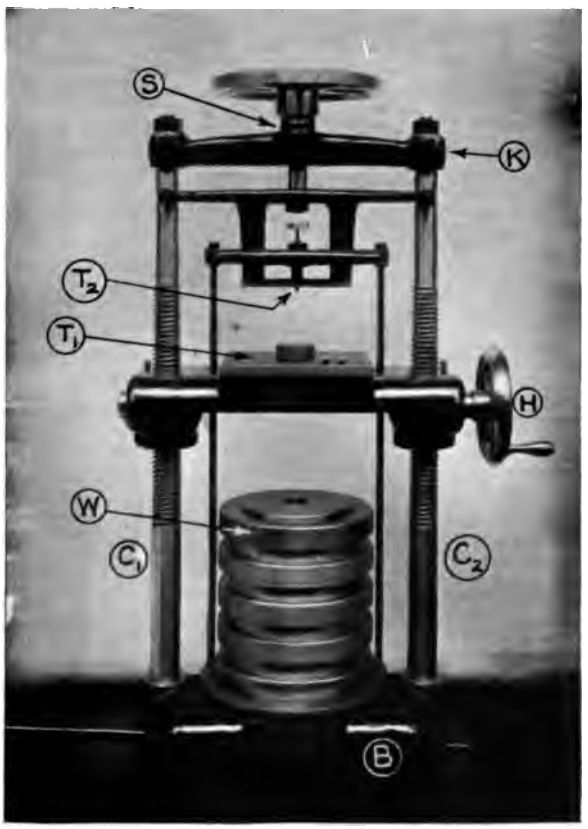

FIG. 194.—Herbert's small Brinell machine.
[*See p.* 282.
[*To face p.* 282.

FIG. 195.—Rockwell hardness tester.

[*To face p.* 283.

The upper hand-wheel is then gently turned until the ball rests upon the specimen, the loading stirrup being free and disconnected from the suspension stirrup. At this stage the whole of the weight is upon the specimen, there being no parts in friction or rubbing contact. The upper hand-wheel is then turned back to take the weight off the specimen, which can then be removed and the diameter of the impression measured, and from this the hardness can be determined.

The overall dimensions of the apparatus are : height 36 inches, width 21½ inches, depth 12½ inches.

(iii) **Rockwell Hardness Tester.**—This is a small hardness tester made by Wilson-Maeulen Co., New York, and is shown in Fig. 195. The principal features in this machine are :—

(i) A ball $\frac{1}{16}$ inch diameter is used for the test.

(ii) The depth of the indentation is recorded by an indicator attached to the machine.

(iii) The apparatus makes two superimposed impressions with loads of 10 and 100 kilograms respectively and indicates the difference in depth between the two impressions.

(iv) The results are not directly comparable with the Brinell hardness number—a new hardness scale is devised.

The load is applied by weights and levers and the even application of the load is insured by independent brake mechanism inside the main casing. To operate the machine, the work is placed on the elevating table (1) and with the hand-screw (H) brought up into contact with the ball and still further up until the dial (D) and index stand at zero, which means that the ball is then under a pressure of 10 kilograms. A button (B) is then pressed, this releases the major load (L, 90 kilograms) which the machine applies gradually. The pointer on the dial moves as the ball sinks into the work and when it reaches its maximum value a crank is turned which operates the rack and pinion (R) and withdraws the major load, leaving the small load of 10 kilograms. The operator then reads the hardness number directly from the dial. The dial has 100 divisions and each division is equivalent to a depth of 0·002 millimetre. 100 on the dial means very hard, while 0 is very soft.

§ 183. **The Ludwik Hardness Test.**—In order to overcome the variation in the Brinell hardness number with load and size of ball Ludwik [21] proposed substituting a 90° cone in place of the ball and this form of indenting tool is now often used on the continent for the softer metals. The hardness number is obtained by means of this test in the same way as with the Brinell test,

i.e. the test load in kilograms is divided by the surface of the conical indentation in square millimetres so that if

P = the load

and d = diameter of indentation

$$\text{Hardness number} = H = \frac{P}{\frac{d}{2}\pi \times \frac{d}{\sqrt{2}}} = 0{\cdot}9\frac{P}{d^2} \text{ approximately.}$$

With this apparatus the hardness number is said to be the same whatever the load chosen if the material is homogeneous.

§ 184. **Measuring Microscopes for Hardness Tests.**—For

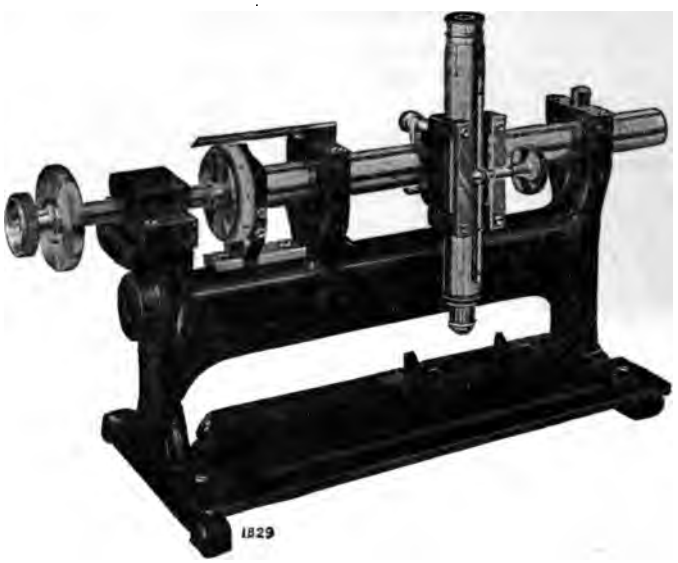

FIG. 196.—The Cambridge measuring microscope.

commercial work the diameter of the indentation is measured to the nearest 0·05 millimetre and for this purpose a microscope with a scale in the eye-piece is usually supplied with the Brinell apparatus. To facilitate the reading of impressions made in corners or below the general surface of the specimen the microscope is sometimes provided with a special adaptable piece.

For research work an accuracy of 0·001 millimetre is essential, and an instrument such as is supplied by the Cambridge and Paul Instrument Co., Ltd., and shown in Fig. 196 is necessary for the purpose. It consists of a microscope clamped to a

tube which is supported by the framework of the instrument and can be traversed by a milled headed screw having a pitch of 1 millimetre. The microscope is fitted with an eye-piece containing cross wires and is provided with a special focussing mechanism.

§ 185. **Depth Indicators.**—In order to dispense with the use of a microscope the depth of the indentation can be measured during the test by means of some form of depth indicator. Instruments of this type, which can be used in any compression machine, are supplied by Alfred J. Amsler & Co., Schaffhausen, or the Scientific Materials Company, Pittsburg.

The depth (h_1), Fig. 188, § 173, is measured relatively to the original surface of the test-piece. This excludes the effect of the extrusion round the indentation and, as the amount of plastic flow varies with different metals and different pressures, the hardness numbers found in this way are not proportional to the Brinell numbers obtained in the usual way from the diameters.

§ 186. **Impact or Dynamic Hardness.**—Numerous methods have been devised for measuring indentation hardness by the size of the indentation produced by energy of known amount. This method is complicated by a consideration of the effect of the rebound of the indenting hammer and there is a difference of opinion as to whether the initial energy of the blow or the net energy absorbed in producing the indentation should be considered in calculating the results.

Edwards and Willis[22] used the initial energy in calculating the results in their research on impact hardness. Unwin,[23] on the other hand, is of opinion "that there should be a single impact and that the energy of rebound should be deducted from the energy due to the height of fall in calculating hardness. He doubted the method of permitting successive impacts till the energy was expended".

A dynamic hardness test was propounded by Martel[24] in 1895. He used a pyramidal point as the indenting tool and produced the indentation by the fall of a ram on to the tool. Martel found:—

(1) That the work of the falling ram was proportional to the volume of the indent, and he therefore expressed hardness as the work required to produce unit volume of indentation.

(2) That for equal energies of blow the volume of the indentation was nearly the same, when using indenting tools of slightly different form.

The authors carried out a series of experiments[13] which

confirmed the first of Martel's conclusions. They showed further that, when using a 10-millimetre diameter ball, the ratio of the dynamic hardness number to the Brinell hardness number was approximately 1·5 over a range of Brinell hardness from 20 to 680. The dynamic hardness number was taken as being equal to the net energy in kilograms divided by the volume of the indentation in cubic centimetres.

The dynamic method is useful for determining the indentation hardness values of metals at high temperatures, under which conditions the standard Brinell test cannot be conveniently carried out. The indenting tool in the dynamic test is in contact with the specimen for such a short interval of time that it is not appreciably affected by the heat.

§ 187. **Dynamic Hardness Testing Machines.**—(i) A moving anvil block is supplied by W. & T. Avery[25] to adapt their Izod pendulum impact machine (see § 196 (i)) for dynamic hardness tests.

(ii) **The Pellin Hardness Testing Apparatus**[26] is made in Paris by Ph. & F. Pellin, and is specially designed for determining the hardness of thin materials. The indentation is produced by a falling bar of known weight having at the lower end a steel ball 2·5 millimetres in diameter. The release of the indenting tool is arranged electro-magnetically.

(iii) **The Auto Punch,** designed by Rudge Whitworth, Ltd., and shown in Fig. 197, is a convenient and serviceable form of impact hardness tester. It was originally designed for testing case-hardened surfaces but has proved valuable in testing materials of every grade of hardness, even pure lead.

It consists essentially of a knurled hollow cylinder (A) from one end of which projects a plunger (B) which ends in an adapter and cap (C) for carrying a ¼-inch hardened steel ball. The other end of the auto punch is closed by a screwed end, in which is fixed centrally a pawl-operating rod (P) ¼ × 3 inches long, the object of which will appear shortly. Behind the sliding hammer is a spring which, in the case of the 12-inch auto punch, requires about 150 lbs. pressure to compress it. A 6-inch auto punch spring requires about 40 lbs. The internal mechanism is shown in Fig. 198. The plunger (B) is reduced to about ¼ inch diameter for about 1·7 inch at its inner end. This part of the plunger is small enough to pass right through the hole in the sliding hammer, and will do so when the sliding pawl is moved sideways by the pawl-operating rod (P) already referred to.

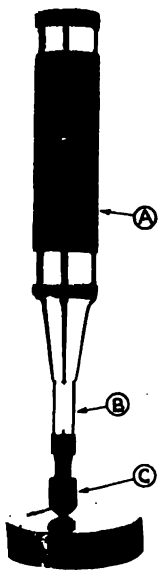

FIG. 197.—The auto punch.
[*To face p.* 286.

When the auto punch is not in use the inner end of the plunger rests on the pawl in the sliding hammer. When the ball is applied to the article to be tested, and the knurled barrel of the auto punch is pressed towards the article, the hammer is forced back, compressing the spring, and continuing to compress it until the taper end of the pawl-operating rod presses the pawl (R) to one side and allows the compressed spring to drive the hammer (H) forward until the front face of the latter strikes the end of the larger diameter part of the plunger. The kinetic energy of the hammer is, of course, nil up to the moment of its release, so that however rapidly or slowly the auto punch may be worked, the energy of the sliding hammer will be the same. This energy will be used up in deforming and heating both the hammer and plunger where these strike one another, and also the specimen and ball. Although the energy of the hammer is practically constant, the proportion of the total energy delivered to the specimen varies according to the hardness of the specimen. The softer the specimen, the greater is the proportion of the total energy spent in deforming the specimen.

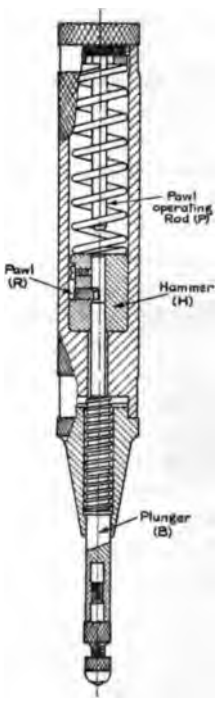

FIG. 198. — "Rudge Whitworth" 12-inch auto punch.

The diameter of the indentations produced by the auto punch follow those produced by the Brinell tests on the same class of material. If a Brinell standard block is employed to check from time to time the readings of the auto punch, the latter instrument can be used as a quick way of ascertaining the approximate Brinell hardness. In cases where an auto punch is used to ascertain whether deliveries are to the specified Brinell hardness it is wiser to use the auto punch as a "workshop" gauge, and to employ the Brinell machine as an "inspection" gauge on all specimens which the auto punch shows to be near one or other of the limits of hardness.

(iv) **The Shore Scleroscope**[27] is a rebound instrument for measuring hardness. A small diamond-pointed hammer about $\frac{3}{4}$ inch long and $\frac{1}{4}$ inch diameter, weighing $\frac{1}{12}$ oz., is allowed to fall freely from a height of 10 inches. The height of rebound of the hammer is measured against a scale graduated into 140

equal parts and is taken as a measure of the hardness. The shape of the diamond striking point is slightly spherical and blunt, being about 0·020 inch in diameter.

The instrument is one which depends on the production of a permanent indentation by this point at the striking surface, the rebound being diminished by the work expended in producing the indentation. With rubber no permanent indentation is produced and the height of rebound is the same as that from a moderately hard steel.

The instrument is provided with an ingenious automatic head by means of which the hammer is lifted and released by air pressure from a bulb.

The scleroscope and Brinell hardness scales[28] have been showed to be generally closely related throughout the hardness range. The Brinell hardness number divided by six is approximately equal to the scleroscope number; the ratio appears to increase from 5·5 for soft steels to 8·0 for materials of over 700 on the Brinell scale. The applications of the scleroscope are therefore similar to those enumerated for the Brinell test in § 175.

The scleroscope readings have been found to be slightly dependent on the size of the piece tested. This variation can be considerably reduced by clamping the test-piece to a firm foundation. An investigation into the methods of supporting light specimens for the scleroscope test has been carried out by Tritton.[28a] Most materials are mechanically hardened by indentation. It is therefore important to ensure that the material is not tested twice on the same place otherwise high results are obtained.

(v) **The J.A.C. Sklerometre.**—A rebound instrument in which a small *ball-ended* hammer is employed has been designed by J. A. Chappuis. It is constructed in the form of a set square, of which the apex of the right angle forms the pivoting point of the hammer. The two sides of the square are joined together by an arc carrying the scale. The hammer is fitted with a little catch which is released automatically by the shock of the blow and which retains it at the highest point of its rebound. The hammer thus traverses an arc and gives a larger range than the shore scleroscope for the harder materials. The instrument is supplied by Chas. Churchill & Co., Ltd., and is called the *J.A.C. Sklerometre.*

(vi) **The Waldo Hardness Testing Apparatus.**—This instrument employs a conical-pointed plummet whose weight is 0·1 lb. The point is replaceable and is made out of chill tempered steel and is ground to an angle of 60°.

The plummet is raised to a height of 12 inches and an arrangement is provided for ensuring that it will fall vertically on to the desired place on the test-piece which is held by the base of the apparatus.

In order to avoid disturbance in the upper support the plummet is released from the bottom of the apparatus by a cord connected to the release at the top. The hardness number is calculated from the diameter of the impression.

It has been shown by Batson [13] that the hardness numbers obtained from an apparatus of this kind will be approximately proportional to the Ludwik cone numbers if they are calculated from the net energy of the blow divided by the volume of the indentation.

§ 188. **Abrasion or Scratch Tests.**—The abrasion test has been applied in three ways :—

(1) As a scratch test.

(2) By drilling or grooving with a hardened steel tool or diamond.

(3) By wearing away with or without an abrasive.

§ 189. **The Scratch Test.**—The scratch test has been frequently used in conjunction with an indentation hardness test. In 1722 Reaumur [2] used both methods. As an indication of scratch hardness he tested metals against a bar whose hardness increased from one end to the other; the position on this bar which the metal under test would scratch indicated its hardness. Mohs [29] was the first to give a scratch hardness scale which is still largely used by mineralogists. Ten minerals were arranged in order from 1 to 10 in such a way that each would scratch the one next below it on the list. Talc was taken as having a hardness of "one" and diamond a hardness of "ten".

(i) **Turner's Sclerometer.**[30]—In this device a balanced lever is—

(1) Provided at its free end with a diamond point fixed in a vertical pencil.

(2) Loaded with a sliding weight and calibrated in order that the sliding weight can be set to represent known weights at the point.

(3) Supported in such a way that it can be rotated.

The hardness number is the smallest weight in grammes which will produce a scratch just visible to the naked eye on the smoothed and polished surface of the specimen.

A series of scratches are made with diminishing weights and the hardness is taken as the mean between the least weight which

will produce a scratch and the greatest weight which will not produce a scratch.

A. Martens[31] in order to make the test more definite defined the scratch hardness number as the load in grammes under which a conical diamond (90°) produces a scratch 0·01 mm. in width. A. L. Parsons further modified the sclerometer by applying the load on the diamond point by a spring in such a way that the pressure increased as the point was drawn across the test-piece. The place at which the scratch commenced was noted and the corresponding load taken as the hardness number.

A special form of scratch testing apparatus made by W. & T. Avery, Ltd., to the design of Prof. Turner and W. E. Allcut has been used by the Research Department of Hadfields Ltd.[32] The apparatus is of a simple character, consisting of a balanced lever arm, fitted with a jockey weight, and carrying at its end a diamond point. The diamond is drawn along the surface of the metal to be tested, thus making a scratch.

The diamond point is pyramidal in shape having four flat sides and is placed in the machine so that two edges are in the line of the scratch. A constant weight of about 170 grammes is employed and the width of the scratch is measured by means of a special measuring microscope in which one division is equal to 0·0175 mm. The results show that the hardness of very hard steel as measured by the scratch test is much higher than is indicated by the Brinell ball hardness method but otherwise the results from the two methods bear a general relationship.

(ii) **The Micro-character**[33] is an instrument developed by the Sub-Committee on Bearing Metals of the American Society of Mechanical Engineers. A hard sapphire point is used which enables the hardness of individual crystals of steel to be tested. A tentative scale of micro-hardness, expressing the relation of the hardness between different materials, has also been arranged.

The instrument is essentially a scratch hardness apparatus. It is mounted on the stage of an ordinary microscope and the sapphire point rests on the etched and polished surface of the material to be tested. The test surface is lubricated with immersion oil. The jewel point is mounted, in a delicate spring directly beneath the point of application of the load. A weight of 3 grammes is used and a slow continuous feed is given to the jewel point by a worm gear. This forms a scratch the width of which gives a measure of the hardness.

§ 190. **The Quadrant Sclerometer.**—This instrument has been devised in the Rudge-Whitworth Laboratory. The method

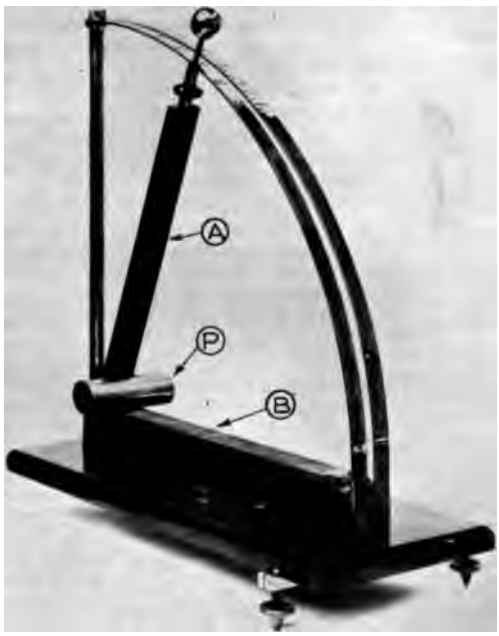

FIG. 199.—The quadrant sclerometer.

[*See p.* 291.

FIG. 200.—Drill hardness testing machine.

[*To face p.* 291.

employed is to apply a hardened edge or series of hardened edges to the surface of the test-piece in such a direction that slipping ensues until they "bite" the surface of the article.

The instrument is made in various types for testing either flat surfaces, pins, or the inside of cylindrical surfaces. Fig. 199 shows a pin under test.

Two specially cut flat rods or files (A and B) are employed, and the upper one (A) is raised until it makes an angle of about 80° with the lower (B). The pin (P) is then placed between them and the "file" lowered until it "bites" the pin. The angle at this point is an index of the scratch hardness of the article.

The theory of the instrument has been worked out by H. L. Heathcote,[34] who has shown that the angle is practically independent of the weight and size of the article to be tested. A soft bar holds the top file up so that it makes an angle of about 70°. A hard bar will not hold the top file up until the angle falls to about 15 to 20°. Hardened and tempered bars give readings between 20 and 70°, according to their surface resistance to abrasion. The instrument can also be employed for measuring the coefficient of friction between one material and another, one being attached to, or substituted for, the upper arm, and the other for the lower.

§ 191. **"Drilling or Grooving" Hardness.**—S. Bottone [35] measured the resistance to wear by the time required to produce, in the material, a cut of definite depth with a soft iron disc rotating at constant speed and pressed with constant force.

A. Haussner [36] defined cutting hardness as the resistance, per sq. mm., to planing, when using a cutting angle of 90°.

Jaggar [37] rotated a diamond point under constant pressure and at a uniform rate and gave the number of rotations of the point to reach a fixed depth as the hardness. Bauer and Keep [38] both defined cutting hardness as the rate at which a steel drill, running at constant speed and under constant pressure, drills the material.

Fig. 200 shows a drill hardness testing machine devised and used by Alfred Herbert Ltd., Coventry. The sample piece to be tested is held in an ordinary small lathe chuck (C) and a horizontal drill (D) is fed into the sample by gravity—note the suspended weight (W). Penetrability is registered on a recording drum (R) and affords a most useful guide as to hardness of cast iron.

§ 192. **Wear Tests (Abrasion).**—(*a*) *Using an Abradant or*

an Abrading Wheel (*Pure Abrasion*).—Felix Robin [39] used cylindrical specimens (50 mm. diameter) which he rubbed under known pressure on papers covered with abrasive powders. Rosiwall [40] defined abrasive hardness as equal to 1/loss of volume, by grinding with an abradant. Behrens [41] used a standard powder and measured hardness by the time required to polish.

Gary [42] determined the resistance to wear by the amount of abrasion caused by a sandblast, and experimented chiefly with stones, artificial minerals and timber. W. H. Warren [43] also used the sandblast on timber.

Jannetaz and Goldberg [44] and Stoughton and Macgregor [45] measured the comparative loss by grinding. The latter, who also

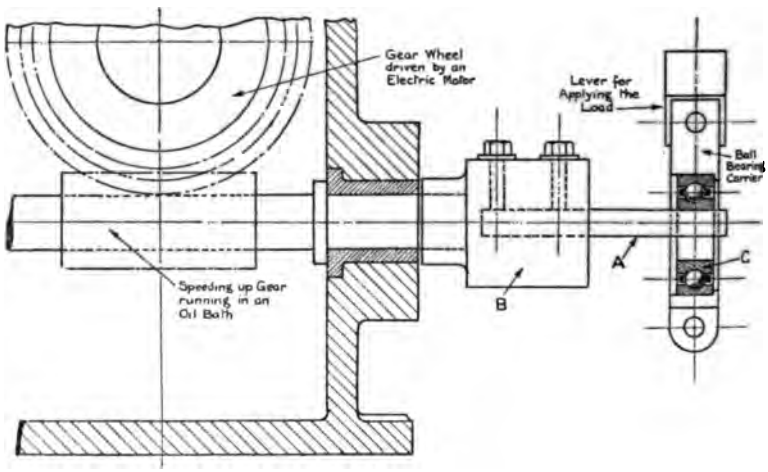

FIG. 201.—Saniter's rolling abrasion test.

carried out indentation hardness tests, found that the two methods gave different comparative results.

(*b*) *Wear by Sliding Lubricated Abrasion.*—Derihon [46] constructed a machine in which a specimen was pressed on to the circumference of a polished wheel turning at a speed of 3200 revolutions per minute in an oil bath. The wear was measured by the loss in weight or reduction in diameter in thousandths of a millimetre after 2,000,000 turns of the wheel.

(*c*) *Wear by Dry Rolling Abrasion.*—Saniter [47] devised a machine for testing the wearing properties of rail steel under dry ROLLING abrasion. In this method the specimen (A), 5 inches long and 0·5 inch diameter, was fixed in a chuck (B, Fig 201)

revolving at 4000 r.p.m. and carried near the free end a ball-bearing (C) of inner diameter 1 inch, loaded to produce a pressure of 205 lbs. at the line of contact. The inner ring of the ball-bearing ($\frac{1}{16}$ inch wide) was rotated by friction by the test-piece causing the latter to wear. The resistance of the material to rolling abrasion was taken as being inversely proportional to the reduction in diameter in ten-thousandths of an inch after 200,000 revolutions of the test-piece.

A similar test was used by Stanton and Batson [48] for a series of experiments on hardness tests. The dimensions of the test-piece, etc., were made slightly larger than those employed by Saniter.

It was shown that the resistance to rolling abrasion was approximately proportional to the ball hardness number, but that the comparison was not a safe one as there were frequently cases in which a considerable departure was found from this ratio, e.g. manganese steel which was well known to be susceptible to hardening under pressure. The results confirmed Saniter's conclusions and showed that what was actually measured was the resistance to disintegration of already deformed material and that this resistance depended on the amount of deformation produced and had little relation to the material in the unstrained condition. The method, as a means of predicting the relative resistance to wear under conditions of rolling abrasion with heavy loads, was comparatively rapid and gave the information desired.

(*d*) *Wear by Dry Sliding Abrasion.*—The Saniter test was carried out with high pressure and VERY SMALL relative motion. Stanton and Batson [48] also carried out a series of tests on DRY SLIDING abrasion in which the amount of relative motion was LARGE and therefore corresponding to the wear of pins, collars, etc. This was done by connecting the abrading ring (diameter = D) to the chuck by means of an Oldham coupling so that both ring and specimen (diameter = d) completed a revolution in the same time, the line of contact remaining fixed relative to the machine. The slip per revolution was then = $\pi(D - d)$ inches. The results indicated that there was very little hardening of the surface of the material under these conditions and that the Brinell hardness number was not a safe guide in predicting the relative resistances to wear of a miscellaneous selection of steel.

Norris [49] carried out a series of tests under dry combined rolling and sliding abrasion in a modification of the Stanton ring fatigue testing machine.[50] The apparatus used by Norris consists of three $3\frac{1}{2}$ inches diameter rollers with the test-piece

between them. The two lower rollers are driven by gears while the third and upper roller, by which the load is applied with a lever, is driven by friction. The two lower rollers are driven at different speeds to produce a slipping of the specimen which has a groove turned on to it to fit into corresponding grooves in the rollers designed to prevent lateral motion.

The test-piece is 2 inches long, $\frac{7}{8}$ inches diameter and weighs about 160 grammes. The load applied is 224 lbs. and the loss of weight of the specimen, after 100,000 revolutions of the driving roller, is measured to an accuracy of 0·1 milligram.

The tests show a general decrease in the amount of wear as the Brinell hardness and strength increase, but the results are very irregular and in some cases softer steels show less wear than the harder ones.

There seems to be a general agreement between investigators as to this irregularity.

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CHAPTER XIX.

IMPACT AND NOTCHED BAR TESTING.

§ 193. THERE is no doubt that the tensile test, as usually carried out, does not give all the information about a material it is essential that an engineer should know. A careful examination of a complete load-extension diagram, however, reveals differences, such as those due to heat treatment and mechanical treatment, not disclosed by an ordinary tensile test, but the analysis of such diagrams requires considerable experience.

It has, occasionally, been found that a material which has satisfactorily passed the ordinary tensile test fails in practice in a manner which cannot be accounted for by errors in design. Investigation has shown that, in some cases, parts of machinery which have failed in this way have been subjected to shocks. Consequently, various methods of test have been devised to give a definite indication of the shock-resisting properties of materials.

§ 194. **Notched Bar Tests.**—Freedom from the tendency to crack at sharp corners, when the variations of stress are considerable, is a property which is very desirable in materials for engineering work. In order to obtain this information about materials, " brittleness " tests in which the test-piece is notched so as to limit the plane of fracture and the contraction of area are employed.

These notched bar tests are made in tension or bending. The test-piece is usually broken by a single blow in impact and the energy of fracture obtained directly from the loss of energy of the striker.

In 1909, Charpy,[1] in a report on impact tests on metals, shows that a static tension test is more efficaciously supplemented by a notched bar bending test than by any other test, and his results seem to indicate that the notched bar bending test gives information regarding the fragility of materials which other tests do not easily furnish. Charpy in the same report shows that materials which give good results with this impact test have

stood well in practice whereas the same class of materials giving low values fail, although the results from the ordinary static tensile test is the same in both cases.

The originator of this method of testing appears to have been M. Barba of Le Creusot who, in 1900, described the results of his experiments on the detection of brittleness in steel by tests on flat specimens notched with a 45° notch on both sides to 0·35 times the thickness, the radius at the bottom of the notch being 0·2 mm. and the total width of the specimen 30 mm. The specimen was fixed in a horizontal position between jaws with the notch directly over the edges of the jaws and having a piece of the specimen 25 mm. long projecting from the jaws. This piece was struck by a falling weight of 18 kilograms. Each specimen was provided with a number of notches at spaces of 25 mm. along the specimen, and by making a series of tests at different heights of fall, it was possible to predict the energy of blow which would just break the specimen.

It was soon realised that this method of testing revealed marked differences in the behaviour of materials which were not detected by the ordinary tensile test, and other investigators (Le Chatelier, Charpy, Frémont, etc.) carried out experiments, the results of which were communicated to the Congress of the International Association of Testing Materials held at Budapest in 1901.

The report of a Commission, appointed at this Congress to investigate the notched bar test, was discussed at the Congress held in Brussels in 1906, but no advance was made in the matter of standardisation except an expression of opinion that the test gave interesting information. The German Association for Methods of Testing Materials thereupon took the matter up and issued a report in 1907 in which they recommended the Charpy method of testing. This consists in the use of a notched specimen 30 × 30 × 160 mm. supported horizontally at the ends on knife edges of given form and struck in the centre, opposite the notch, by a pendulum. The notch was formed by drilling a hole 4 mm. diameter in the bar and sawing through from one side, leaving a depth of 15 mm. behind the notch, as shown in Fig. 202. The span is 120 mm.

The question of notched bar testing was again brought forward at the International Congress held at Copenhagen in 1909, who recommended the 30 × 30 × 160 mm. Charpy test-piece with an alternative smaller specimen, geometrically similar but one-third of the size, where the larger dimensions could not be

obtained. The matter was further discussed at New York in 1912, and the recommendations of 1909 were confirmed. No particular machine for carrying out the tests was selected but further research on testing apparatus and test-pieces of different sizes was suggested as being desirable.

The recommendations of the International Association for Testing Materials have never been fully recognised. For most test work the standard 30 × 30 × 160 mm. test-piece has been found to be too large and difficulties have been experienced with the notch of the geometrically smaller test-piece.

Frémont suggests a test-piece 10 × 8 × 30 mm. placed horizontally on supports 21 mm. span with a notch 1 mm. deep and 1 mm. wide (square shape, and made on the broad side at the centre of the length), Fig. 203.

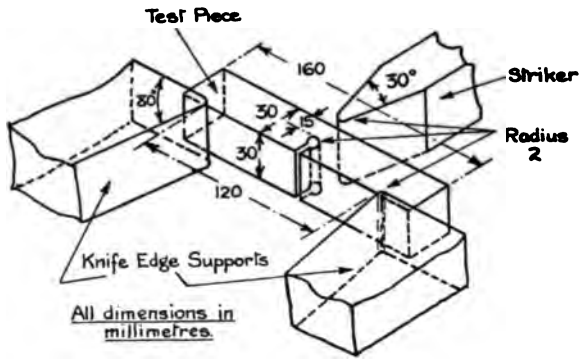

FIG. 202.—Charpy notched bar test-piece. This size of test-piece has *not* been standardised by the British Engineering Standards Association.

In most cases a test-piece 10 × 10 mm. in cross section is used but the form of notch is varied. Several well-known types of notch are given in Fig. 203. The beam test-pieces are usually 60 mm. long with a span of 40 mm.

§ 195. **Notched Bar Testing in Britain.**—A considerable amount of work has been carried out, in Britain, on the notched bar test. Yarrows developed a notched bar test in 1902, in which the test-bar was broken by more than one blow. Valuable information appears to have been obtained by this test, as to the brittleness of steels used for connecting rod bolts.

In 1903, Izod [2] introduced a single blow notched bar testing machine in which the specimen is held in a vice at one end and is struck by a falling pendulum at the other. This method is the

one which is commonly adopted in this country at the present time.

Seaton and Jude [3] carried out some tests in 1904 in which the test-piece was broken by a number of blows, the test-bar being reversed between successive blows.

In 1908, Stanton and Bairstow [4] and Harbord [5] communicated results of experiments to the Institution of Mechanical Engineers. The main point brought out by Harbord's paper was the variability in the results of individual tests of specimens of the same material. It was shown that two identical test-

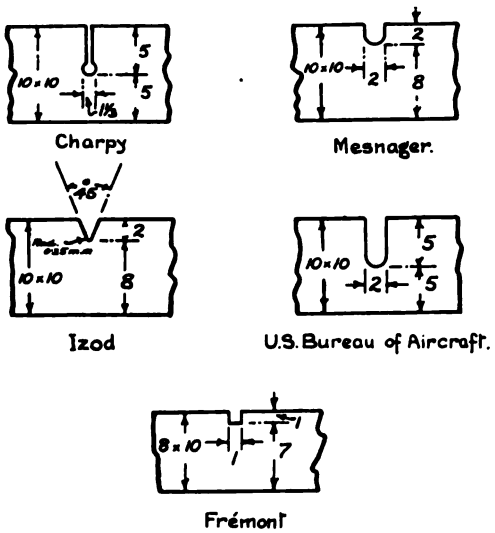

FIG. 203.—Forms of notches for notched bar tests.

pieces from the same bar of ordinary commercial steel gave results varying from each other by over 60 per cent. This variability has been attributed to :—

(1) The mode of testing.

(2) The heterogeneity of the material under investigation.

Experiments published by Charpy and Cornu Thenard [6] show that by careful selection and heat treatment it is possible to obtain, in the course of experiments in notched bar tests carried out on bars of steel of different natures or copper, a degree of uniformity analogous to that obtained by means of tensile or

hardness tests. Variability in the results is therefore not due to the mode of testing but to differences in the material under test.

By 1914 there was conclusive evidence that there could be large variations in the resistance of notched specimens of different materials to impact without any corresponding variation in any of the characteristics brought out by the ordinary tensile test, and there was evidence that this variation was due to correct or incorrect heat treatment.

§ 196. **Impact Testing Machines.**—Two forms of impact test-piece have been standardised in Great Britain (see § 198). The test-piece is either broken as a beam or as a cantilever.

The principal types of machine used for the test are :—

(1) **The Izod Test.**—The Izod impact test has of recent years come into great prominence in government specifications owing to the great demands made by war conditions.

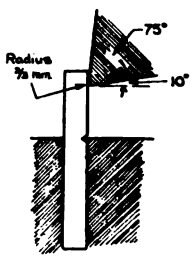

FIG. 205.—Sketch of the striker of the Izod machine showing the angle and radius and inclination of the striker to the horizontal.

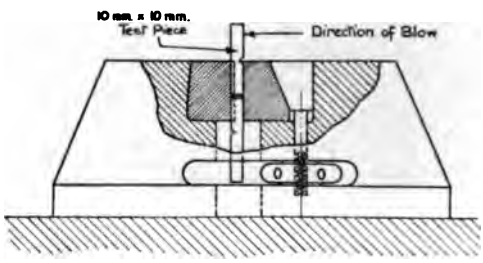

FIG. 206.—Grips for Izod testing machine.

The original Izod machine had a striking energy of the hammer of 23 ft.-lbs. and the test-piece was 2 inches long, $\frac{3}{8}$ inch wide, and $\frac{3}{16}$ inch thick with a V notch 0·05 inch deep.

The present standard machine made by W. & T. Avery, Ltd., Soho Foundry, Birmingham, has a capacity of 120 ft.-lbs. The cross section of the test-piece is 10 × 10 mm. and it is notched with a 45° V notch, 2 mm. deep with a root radius of 0·25 mm. The machine is shown in Fig. 204 and consists of a heavy base on to which are bolted two standards supporting the pivot of the pendulum. The pendulum swings on ball-bearings and strikes the specimen held in the vice, *Cantilever Fashion*, its point of contact with the specimen being a hardened steel knife edge. The form and angle of the knife edge is shown in Fig. 205. The specimen is gripped in a vice in such a posi-

3324

FIG. 204.—The Izod notched bar impact testing machine.

[*To face p.* 300.

tion that the bottom of the notch is level with the top of the vice, the notch facing the direction of the blow, Fig. 206.

The specimen, in being broken, absorbs some of the energy from the pendulum which is measured by the continued and

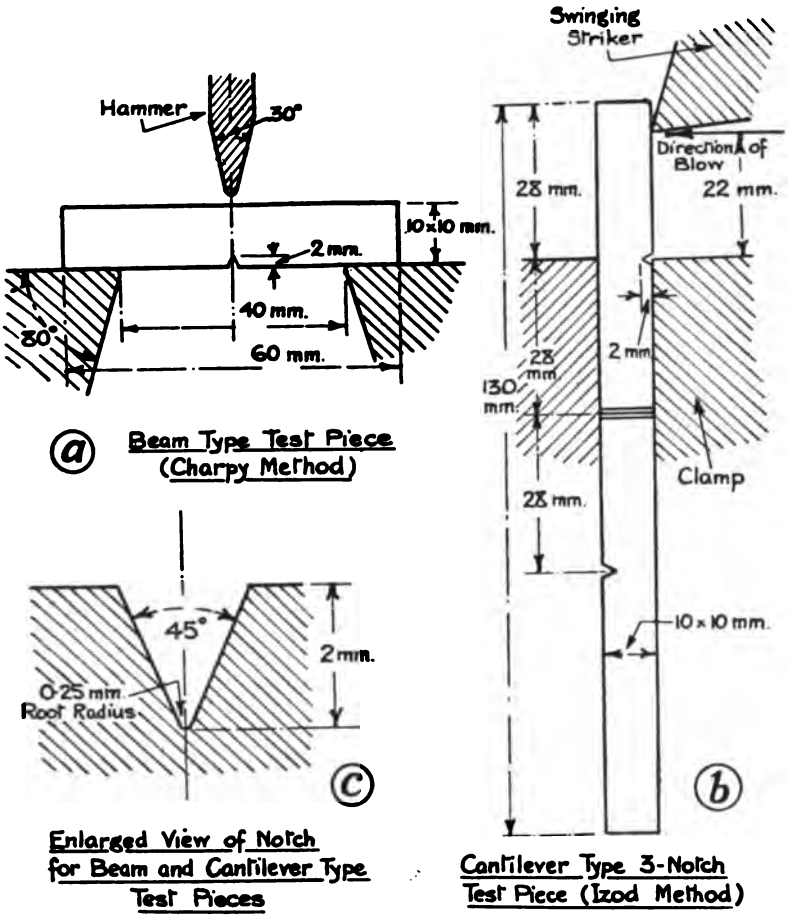

FIG. 207.—B.E.S.A. standard beam and cantilever notched bar test-pieces.

diminished swing of the pendulum moving an idle pointer over a graduated scale. The pendulum swings less as the resistance of the specimen is greater. The scale is graduated to give the actual energy in ft.-lbs. absorbed during the blow. The standard three notch test-piece for the Izod machine is shown in Fig. 207(*b*).

(2) **The Charpy Pendulum Machine.**—The small Charpy machine has a power of about 30 kilogrammeters (217 ft.-lbs.) and a maximum striking velocity of 5·28 metres per second (17 ft. 4 ins. per sec.). The principal part of the pendulum consists of the hammer (M), shaped as shown in Fig. 208, and suspended at the end of a light hollow bar. The centre is sus-

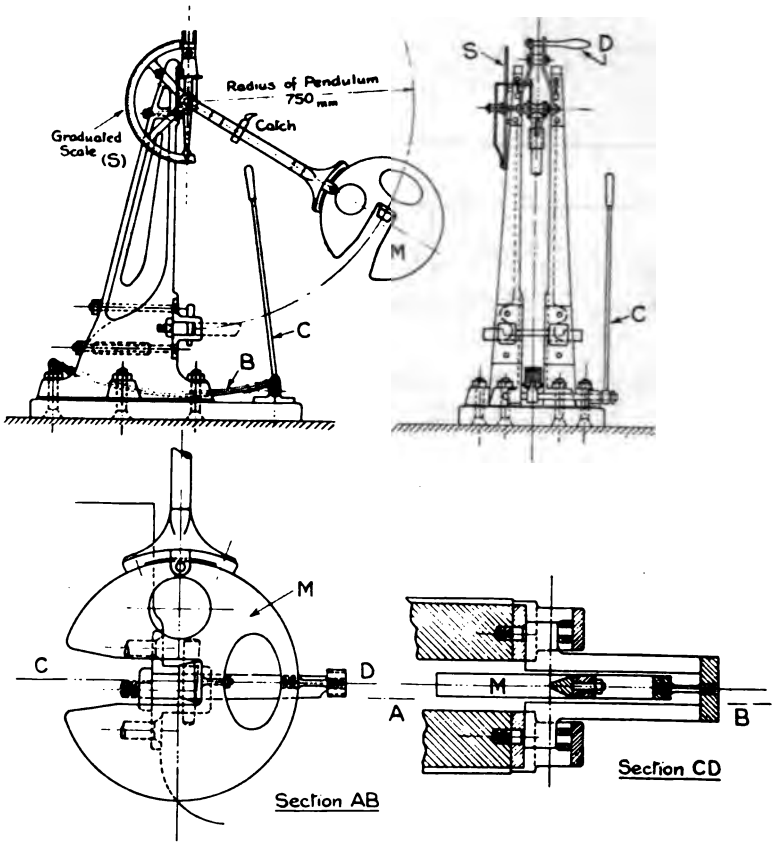

FIG. 208.—Charpy impact testing machine.

pended on ball-bearings, and an index hand is mounted with an easy frictional fit and travels over a graduated semicircular dial with the hammer when this rises up after fracturing the test specimen. The latter is held in cast-iron supports in the two uprights which are bolted down to a cast-iron bedplate.

The hammer is raised up for action by hand and is held up

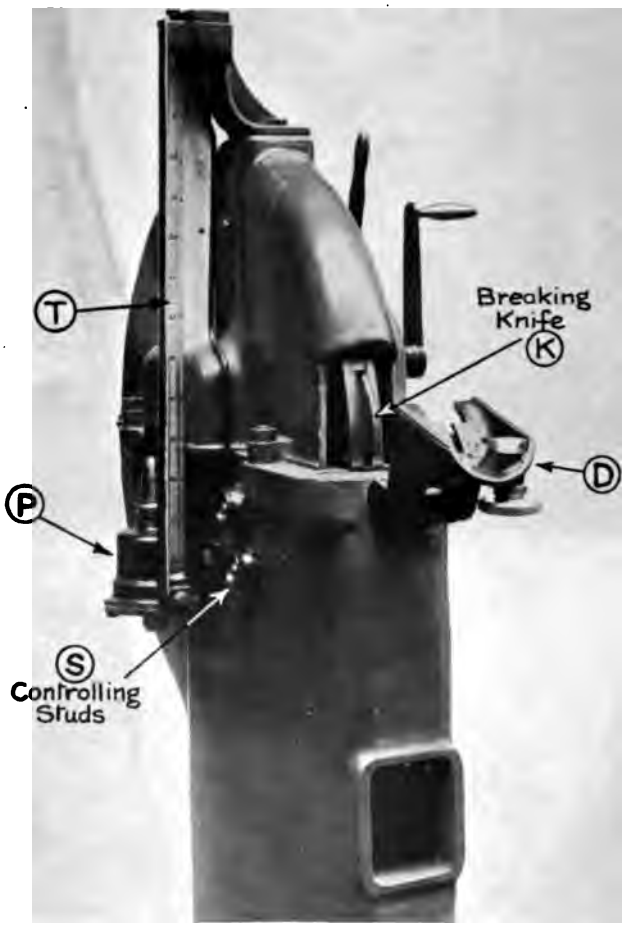

FIG. 209.—The Guillery notched bar impact machine.

[*To face p.* 303.

by a catch operated directly by a small lever (D). The drop is constant and 1·420 metres (4 feet 7⅝ inches) in height. A hand-brake (B) worked by the hand-lever (C) enables the hammer to be stopped rapidly after fracture of the specimen. The weight of the falling parts, position of the centre of gravity, and heights of drop counted from the centre of gravity, are all determined experimentally. The angle of rise after fracture is read off from the graduated sector. The difference between the height of fall before fracture and rising back after fracture gives the work absorbed. It is, however, necessary to take into account the friction and energy absorbed by the fragments of the test specimen, the latter may be considered to take the same velocity as the pendulum itself. The weight of the test specimen being very light compared with that of the pendulum hammer, the correction is very slight and can be neglected in ordinary practice.

In order to determine the work absorbed by friction the pendulum is caused to oscillate freely and the decrease in the oscillations due solely to friction is noted down; this gives a table of corrections. The required correction can also be arrived at by noting the angle of rise of the pendulum following that causing the fracture.

A larger machine is made and this has 200 kilogrammetres energy and a striking velocity of 7·8 metres per second.

(3) **Guillery Machine (Rotary Tup).**—The latest model of this machine is shown in Fig. 209. It consists of a flywheel having a "breaking knife" (K) attached to it. This knife is arranged so that it can assume two positions:—

(1) Flush with the rim of the wheel.

(2) Projecting from the rim of the wheel, in which position it is required for breaking the test-piece.

The position is controlled by "studs" (S) on the casing of the machine and operated by centrifugal force due to the rotation of the wheel.

The rotation of the flywheel also operates a small centrifugal pump (P) which elevates a coloured liquid in a tube (T). The machine is designed so that when the liquid is at the top of the tube (and reading zero on the energy scale) there is 60 kilogrammetres of energy in the flywheel. When the flywheel is still and the liquid is at its lowest level the reading is therefore 60.

The test-bar is placed horizontally on knife edges which have a 40 mm. gap. The front of the machine is covered with a door (D) which is automatically locked when the "knife" is out and the flywheel in motion.

The test is made by rotating the flywheel to a speed slightly in excess of that corresponding to the zero of the energy scale. The gear is then disconnected and the wheel speed allowed to decrease. Immediately the liquid in the tacheometer tube reads zero the "out" stud is pressed, the knife springs out and breaks the test-piece. The absorption of energy from the flywheel lowers the speed and the tacheometer reading gives the energy lost in producing fracture of the test-piece. The knife is then returned by pressing the "in" stud.

(4) **Frémont Machine.**—The Frémont impact machine consists of a hammer of 10 to 15 kilograms, which has on its under side a hardened steel V-shaped striker. The test-piece is placed horizontally on knife edges having a gap of 21 mm. so that when the hammer falls from a height of 4 metres the striker hits it midway between the supports and exactly opposite to the notch.

Immediately after the blow of the striker the under side of the hammer, which then only possesses the energy not absorbed by the test-piece, strikes against an anvil carrying two housings provided with tempered steel springs. The springs yield under the blow of the hammer and register by their deflection the energy remaining in the apparatus.

Knowing the initial energy of the hammer, the energy absorbed in fracture of the test-piece is found by taking the difference.

(5) **The Amsler 75 Kilogrammetre Pendulum Impact Testing Machine.**—This machine is on the same principle as the Charpy machine but some of the details are slightly different.

The pendulum is held up by a hook attached to a rope which is wound round a windlass. The tup is released by detaching the hook by means of a special release, and falling freely swings up on the other side of the machine after having broken the test-bar. Instead of swinging back again, as in the Charpy machine, it is held in position by a cord passing round a drum and acting as a brake.

On falling from one side transverse (bending) tests are made while tensile tests are made when the pendulum falls from the other side. The energy in the hammer before and after the test is registered on two movable straight scales by the movement of the pendulum. It is so arranged that the second scale raises the pointer on to the first scale and indicates the actual energy absorbed.

§ 197. **Further Particulars of Notched Bar Tests.**—The

leading particulars of the five principal types of notched bar machines are given in Table LIX.

TABLE LIX.

Type of Machine.	Striking Energy. Kg. M.	Striking Velocity. Metres/Sec.
Charpy (pendulum) . .	30	5·3
Amsler (pendulum) . . .	75	—
Izod (pendulum) . . .	16·6	3·5
Frémont (falling tup) . .	20 or 60	8·85
Guillery (rotary tup) . .	60	8·85

The notched bar test is principally used as a means of detecting a dangerous condition of microstructure due to faulty heat treatment.

The large variation in the energy absorbed in the Izod test due to alteration of heat treatment is well shown by the figures in Table LX taken from a paper by Philpot.[7]

TABLE LX.

IZOD TESTS ON MATERIALS CORRECTLY AND INCORRECTLY HEAT TREATED.

Materials.	Heat Treatment.	Limit of Proportionality. Tons/Sq. In.	Yield Point. Tons/Sq. In.	Ultimate Stress. Tons/Sq. In.	Elongation. Per Cent.	Reduction of Area. Per Cent.	Average Izod Figure. Ft.-lbs.
Nickel chrome steel							
Bar SS_1 . .	Correct	40·4	47·8	55·5	28·6	64·0	78·0
Bar SS_2 . .	Incorrect	39·6	45·9	54·3	26·5	63·7	9·1
Nickel chrome steel							
Bar SH_1 . .	Correct	34·8	44·0	59·3	26·0	61·9	62·1
Bar SH_2 . .	Incorrect	34·8	45·0	60·3	23·0	44·2	8·0
Nickel chrome steel							
Bar SS_3 . .	Correct	26·0	44·0	54·9	26·0	67·0	81·7
Bar SS_4 . .	Incorrect	35·2	44·0	54·3	24·5	64·0	14·8
Nickel chrome steel	Correct	32·3	44·3	55·2	26·7	69·5	79·5
	Incorrect	31·9	42·1	53·8	29·4	68·5	15·9

Some tests by the authors on a piece of boiler plate and nickel chrome crank shaft are given in Table LXI, and show the same kind of variability with heat treatment.

TABLE LXI.

CHARPY TESTS ON MATERIALS CORRECTLY AND INCORRECTLY HEAT TREATED. (CHARPY METHOD—IZOD NOTCH.)

Materials.	Heat Treatment.	Limit of Proportionality. Tons/Sq. In.	Yield Point. Tons/Sq. In.	Ultimate Stress. Tons/Sq. In.	Elongation. Per Cent.	Reduction of Area Per Cent.	Energy to Fracture. Kg. M.
Boiler plate . .	Correct	18·3	19·1	27·9	42·2	62·8	6·35
	Incorrect	14·2	18·3	26·9	31·6	59·1	0·88
Nickelchrome crank shaft . . .	Correct	27·0	33·0	45·2	21·0	59·2	10·74
	Incorrect	20·0	32·9	44·0	23·5	57·0	2·27

The notched bar test is unsatisfactory if applied to laminated material when the notch is parallel to the laminations. The material tends to split along the fibres giving a jagged fracture. The energy absorbed in fracture in such a case is always high. The results in Table LXII of two materials of nearly similar composition and mechanical strength show that the test-pieces with a laminated structure require four times as much energy to break them.

TABLE LXII.

NOTCHED BAR TESTS ON THE STANDARD BEAM TEST-PIECE.

	Tensile Test.		Notched Bar Test.	
	Ultimate Stress. Tons per Sq. In.	Elongation Per Cent. Gauge Length $= 4\sqrt{\text{Area}}$.	Energy Absorbed in Fracture in	
			Kilogrammetres.*	Ft.-lbs.*
Laminated material	42·3	30·0	15·5	111·9
Normal material .	37·5	32·0	3·78	27·4

* Average of three tests.

Bagnall-Wild has shown that the brittleness in steel resulting from a high percentage of sulphur and phosphorus is well marked by the Izod test. He says, "Certain steel for making nuts and bolts was found to contain sulphur and phosphorus in excess of 0·1 per cent.; such steel invariably failed to give any higher reading than 2 to 3 ft.-lbs. on the Izod, whereas a steel of exactly

similar composition and with similar treatment but with sulphur and phosphorus below 0·06 per cent. gave an Izod test figure of over 40 ft.-lbs.".

§ 198. **Dimensions of Standard Test-pieces.**—Although there are several impact testers in Britain of the Frémont and Guillery type, the majority of test houses use Izod or Charpy machines. The dimensions of test-pieces for these machines have been standardised and are shown in Fig. 207 (page 301). It will be noted that in each case the cross-sectional dimensions are 10 × 10 mm. and that the form of notch is the same. (The Guillery machine uses the same size of test-pieces as the Charpy machine while the Frémont test-piece is smaller and is described in § 194, page 298.) The form of notch selected and sometimes called the Izod notch, is a 45° V, 2 mm. deep with a root radius of 0·25 mm.

§ 199. **The Angle of the Notch.**—Experiments by Thomas[8] at the Watertown Arsenal show that, with mild steel, the angle of the notch does not appreciably affect the results until it has exceeded 45°. The results that Thomas obtained are given in Table LXIII.

TABLE LXIII.

EFFECT OF VARIATION OF ANGLE OF NOTCH ON THE ENERGY ABSORBED.

Angle of Notch. Degrees.	Charpy Impact Values. Ft.-lbs. per Sq. In.			Angle of Bend. Degrees.	Brinell Hardness Number.
	Maximum.	Minimum.	Average of 6.		
0	304	266	285	15·8	79
15	346	283	316	15·2	77
30	323	284	298	15·0	81
45	382	304	334	29·5	80
60	571	516	539	54·2	80
75	890	818	854	130	78
90	830	806	814	136	78

§ 200. **Root Radius and Depth of Notch.**—The 10 × 10 mm. test-piece in which the notch is formed by a drilled hole 1⅓ mm. diameter, proposed by the International Association of Testing Materials, cannot be produced economically on the majority of alloy steels.

The form of notch selected as a standard, viz. 45° V notch, 2 mm. deep and 0·25 mm. root radius, does not suffer from this objection as it can be easily produced even on the hardest steels.

The shape at the bottom of the notch has an important effect on the work absorbed in fracture which has its least value when the angle at the bottom of the notch is as nearly zero as possible.

Results by Dix [9] summarised in Table LXIV and by the authors (Table LXV) show this effect very clearly.

TABLE LXIV.

EFFECT OF RADIUS AT THE BOTTOM OF THE NOTCH ON THE ENERGY ABSORBED IN FRACTURE.

Nickel Chrome Steel Rod ½-in. in Diameter.

Form of Notch.	Energy Absorbed in Fracture. (Charpy Machine.)	
	Ft.-lbs.	Kg.M.
2 mm. deep (45° V) sharp	21·6	2·99
2 mm. deep (45° V) 0·25 mm. root radius .	25·0	3·46
2 mm. deep (parallel sides) 1 mm. root radius	40·3	5·57

TABLE LXV.

0·65 *Per Cent. Carbon Steel—V Notches 2 mm. Deep.*

Root Radius of Notch in mm.	Energy Absorbed in Fracture. (Charpy Machine.)	
	Ft.-lbs.	Kg.M.
Sharp	4·05	0·56
0·17	6·86	0·95
0·34	8·31	1·15
0·68	13·7	1·89

It has been found that the sharper the notch is made, the better the test discriminates between brittle and tough materials, that is to say that as the material tested becomes tougher the effect of alteration of the root radius is less.

It is unsatisfactory, commercially, to standardise a dead sharp notch as it is difficult to be always sure that it is produced. A root radius of 0·25 mm. has been selected as it is found that, with a radius of this size, the test is still effective in the detection of faulty heat treatment.

It has also been found that shallow notches increase the energy to fracture of tough materials relatively to that required for brittle materials.

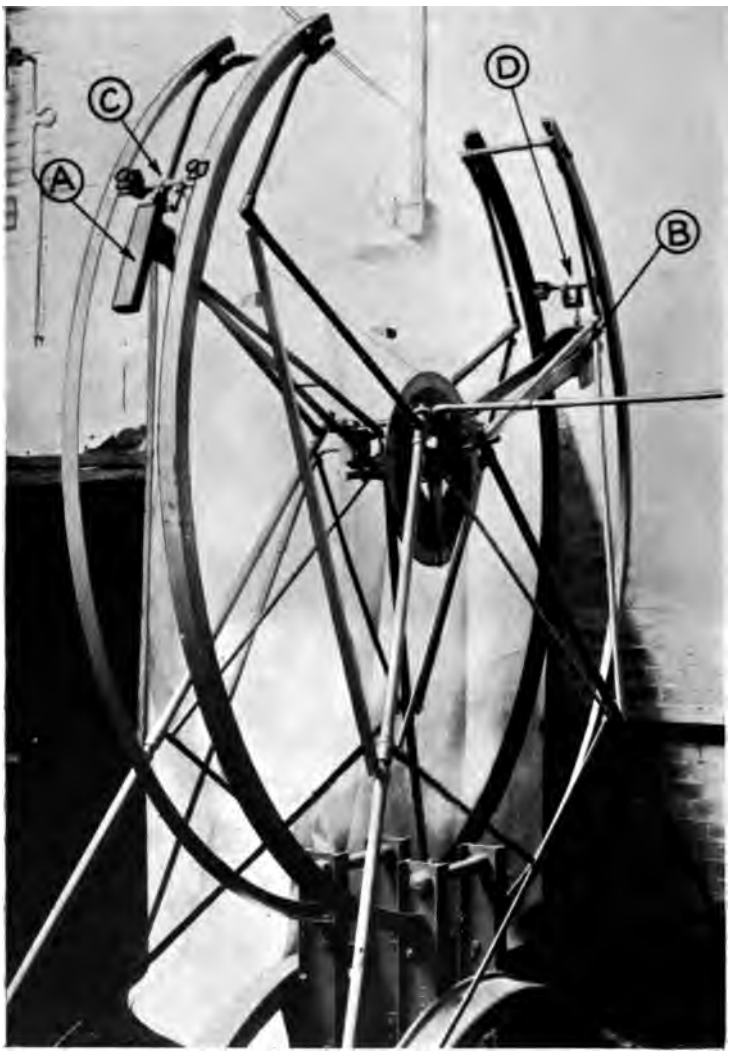

FIG. 210.—High velocity impact machine.

[*To face p.* 309.

§ 201. **Shape of Test-piece.**—Philpot[7] found that a round test-piece can be produced which can be used for acceptance tests on heat-treated steels in place of the standard square specimen. The latter is, however, far the more desirable from the point of view of testing and, by properly rigging up for quantity production, it can be prepared by a pair of straddle mills just as economically as the round test-piece.

§ 202. **Comparison of Tests on Different Machines.**—Philpot[7] has made a comparison of tests in the Charpy (beam) and Izod (cantilever) machines on the standard 10 × 10 mm. test-piece with the 45° standard notch, 2 mm. deep and 0·25 mm. root radius. He finds that, where the energy absorbed is less than 70 ft.-lbs., notched bar tests, made in either the Charpy or the Izod machines, give similar values but where the energy absorbed in fracture is greater than 70 ft.-lbs. there is a tendency for the values from the Charpy machine to be somewhat higher.

Charpy and Cornu Thenard[6] have made a series of experiments, with a steel specially prepared to give consistent results, on "beam" machines of three different types (pendulum, vertical drop, and rotary) and have found that, in regard to energy absorbed in fracture, the results are practically identical when the size of test-piece, notch, distance between supports and radii of supports and striker are uniform.

§ 203. **Effect of Striking Velocity on the Energy to Fracture.**—Both Belanger and Frémont have found a variation of the energy absorbed in fracture with striking velocity but in opposite directions. Charpy has found that the influence of the rate of impact is practically negligible within limits which do not exceed those of appliances generally employed in the testing laboratory.

Some tests carried out by the authors show that, on a machine of the Charpy type at striking velocities up to 43 feet per second, increasing the striking velocity may either increase, decrease, or unalter the energy absorbed in fracture according to the material upon which the tests are made. In any case the effect is not appreciable until after a velocity of 16 feet per second is reached, as is shown by the results in Table LXVI.

As the machine used for these tests is of rather unusual design it is shown in Fig. 210. It consists of a pendulum hammer (A) and pendulum anvil (B), both of which are released at the same time from triggers (C and D) at opposite sides of the machine and pass each other when at the bottom of their

swings. The moments (i.e. weight × distance of the centre of gravity from the axis) of both the hammer and the anvil are the same, the hammer being made of steel and the anvil of cast light alloy with steel knife edges for the test-piece to rest on. The test-piece is clipped on to the anvil knife edges in such a way that no resistance is offered by the clip to the free fracture of the specimen.

TABLE LXVI.

EFFECT OF STRIKING VELOCITY ON THE ENERGY ABSORBED IN FRACTURE.

Material.	Energy Absorbed in Fracture.		Striking Velocity.	
	Kg.M.	Ft.-lbs.	Metres/Sec.	Ft./Sec.
Mild steel	4·03	29·1	2·7	9
	3·83	27·7	4·9	16
	2·77	20·0	6·1	20
	2·00	14·5	8·8	29
Iron	2·90	20·9	4·9	16
	2·80	20·2	6·6	21½
	1·47	10·6	13·1	43
Nickel chrome steel . .	4·00	28·9	2·7	9
	4·40	31·8	4·9	16
	5·44	39·3	13·1	43
Medium carbon steel .	1·03	7·5	2·7	9
	1·05	7·6	6·1	20
	1·05	7·6	13·1	43

The striking velocity in feet per second (where the anvil is fixed) $= 8\sqrt{H(1 - \cos a)}$;

where H = the distance from the axis of the machine to the centre of the test-piece;

and a = the angle that the pendulum makes with the vertical at the release point.

By doubling the length of the pendulum (i.e. doubling the value of H) the striking velocity is increased by about 41½ per cent. whereas by swinging both the hammer and the anvil the striking velocity is the combined velocities of the hammer and anvil when at their lowest points and gives an increase in the striking velocity of 100 per cent.

§ 204. **Method of Calculating the Energy Absorbed by the Test-piece when Using Pendulum Machines.**—Standard machines are supplied with scales engraved in energy units so

that the energy absorbed in fracture is obtained directly from the scale reading.

(i) *Machines with Swinging Hammer and Fixed Anvil.*—With machines of this type the energy absorbed in breaking the test-piece is equal to the difference between the energy in the hammer before and after impact. A correction is necessary for the energy absorbed in friction in the machine bearing, in the pointer or scale indicating arrangement and in moving the broken test-piece.

Referring to Fig. 210A,

if W = the weight of the striking hammer
L = the distance of its centre of gravity from the axis
α = initial angle of the pendulum hammer
β = angle after fracture

then initial energy in hammer = $W(ab) = W(L - L\cos\alpha)$
$= WL(1 - \cos\alpha)$

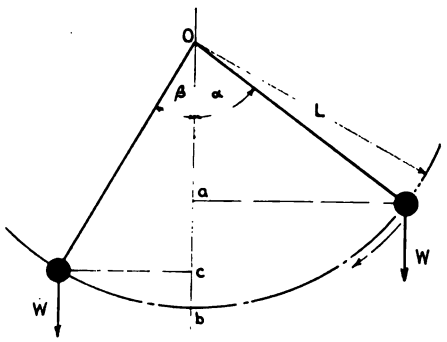

FIG. 210A.

similarly the energy in the hammer after fracture
$= W(cb) = WL(1 - \cos\beta)$

the reduction of energy in the hammer
$= WL(1 - \cos\alpha) - WL(1 - \cos\beta)$
$= WL(\cos\beta - \cos\alpha)$. . . equation 1.

The correction to be applied for the energy lost in friction is obtained by operating the machine as in an actual test but without using a test-piece. The energy lost is given from equation 1 by substituting the values obtained for α and β.

When carrying out the test for this correction care should be taken to see that the pointers and release are operated in exactly the same way as during an actual test.

The broken test-piece can be assumed to leave the machine at the same velocity as the hammer, and the energy given to these pieces is calculated from the formula $e = wH(1 - \cos \beta)$ where e = energy given to the broken test-piece

w = weight of the test-piece or part of the test-piece that leaves the machine

H = distance of the test-piece from the axis of the machine

β = the angle to which the hammer swings after fracture of the test-piece.

This correction is very small in the majority of tests and is seldom applied in commercial testing. Some tests carried out by the authors show that the assumption on which the calculation is based is substantially correct.

(ii) With machines in which the anvil swings, the energy given to or absorbed by the anvil is calculated in a similar manner and due allowance made in calculating the actual energy absorbed by the test-piece.

At the present time the results are usually given in either kilogrammetres or foot-lbs. The dimensions of the standard test-piece are in metric units, so that it would seem consistent to also give the final result in metric units. Until this is, however, universally adopted it is advisable to report results in both systems of units.

§ 205. **Calibration of Impact Machines.**—The most satisfactory method of calibrating an impact testing machine is to obtain the values directly from the weights, angles and dimensions of the machine.

For making a direct comparison with a machine of known accuracy the following method has been used successfully by the authors on several machines.

A bar of mild steel of uniform quality is obtained and carefully normalised. A series of *unnotched* test-pieces are prepared of suitable sizes to absorb energy over the full range of the machine. For a Charpy or Guillery machine the pieces can be made 60 mm. long, 10 mm. wide, and of depths varying from 2 to 10 mm. in increments of 1 mm. At least three test-pieces of each size are tested in the "Standard" machine and also in the machine to be calibrated. From the average results a record is obtained of the accuracy of the latter and a correction-curve can be drawn.

It is found that, with unnotched test-pieces of suitable mild steel, the results are consistent.

If K = the actual energy absorbed by the test-piece
d = the depth of the test-piece
c = a constant
then if the other dimensions of the test-piece do not vary

$$K = cd^n.$$

and n has a value slightly greater than 2.

Table LXVII are the results obtained by this method in a Charpy machine known to be accurate. These are plotted in

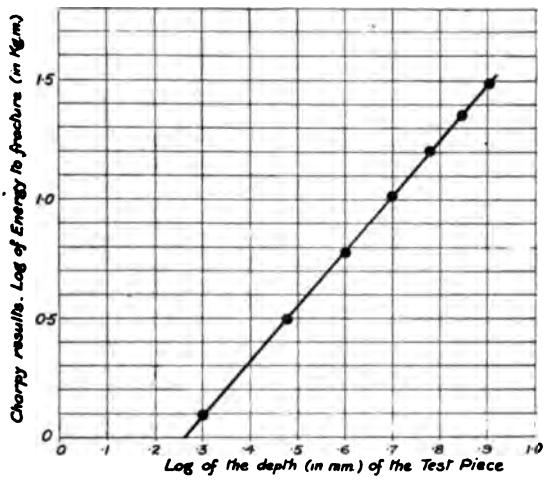

FIG. 211.

Fig. 211 with log. K as ordinates and log. d as abscissæ. The curve is seen to be straight and the value of n = 2·3.

TABLE LXVII.

TESTS ON UNNOTCHED SPECIMENS OF MILD STEEL IN STANDARD CHARPY MACHINE.

Size of Test-piece.			Energy Absorbed in Kilogrammetres.					
Depth.	Width.	Length.						Average.
mm.	mm.	mm.						
2	10	60	1·26	1·23	1·26	1·28	1·23	1·25
3	10	60	3·11	3·16	3·09	3·07	3·12	3·11
4	10	60	6·08	5·81	6·16	5·94	6·08	6·0
5	10	60	9·88	10·43	10·37	10·37	10·51	10·3
6	10	60	16·04	16·11	16·38	15·92	15·84	16·05
7	10	60	23·30	22·7	22·9	22·6	21·7	22·6
8	10	60	30·6	30·8	30·6	30·4	30·6	30·6

Table LXVIII gives the energies recorded on the same steel by a Guillery machine, and Fig. 212 shows the Guillery results plotted against the Charpy results. This curve indicates that (assuming the Charpy results to be correct, as they undoubtedly were) the scale of this particular Guillery machine is incorrect.

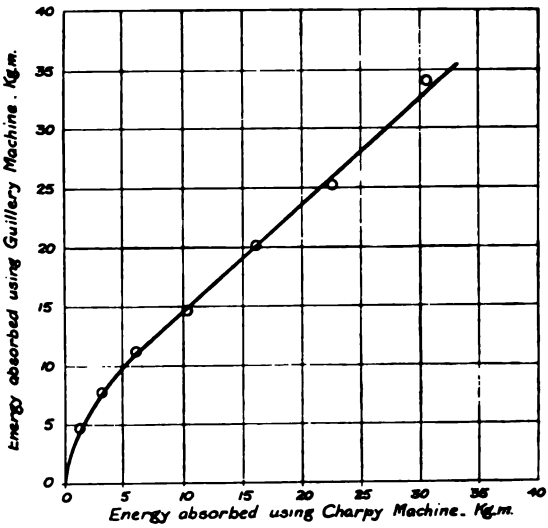

FIG. 212.—Comparison of Guillery and Charpy machines.

TABLE LXVIII.

TESTS ON UNNOTCHED SPECIMENS OF MILD STEEL IN A GUILLERY MACHINE.

Size of Test-piece.			Energy Absorbed in Kilogrammetres.		
Depth.	Width.	Length.			Mean.
mm.	mm.	mm.			
2	10	60	4·8	4·7	4·75
3	10	60	7·7	7·8	7·75
4	10	60	11·2	11·2	11·2
5	10	60	14·4	14·9	14·65
6	10	60	20·2	20·0	20·1
7	10	60	25·7	24·8	25·25
8	10	60	34·0	34·1	34·05

§ 206. **Slow Bending Tests on Notched Bars.**—It has been shown by Philpot[7] and others that, if a notched bar test-

piece is broken slowly, the work expended is comparable with that measured by an impact machine (at moderately low striking velocities) and is equally as effective in distinguishing between certain brittle and tough materials.

As an average of a large number of tests Philpot found that the energy absorbed in the slow bending test is about 75 per

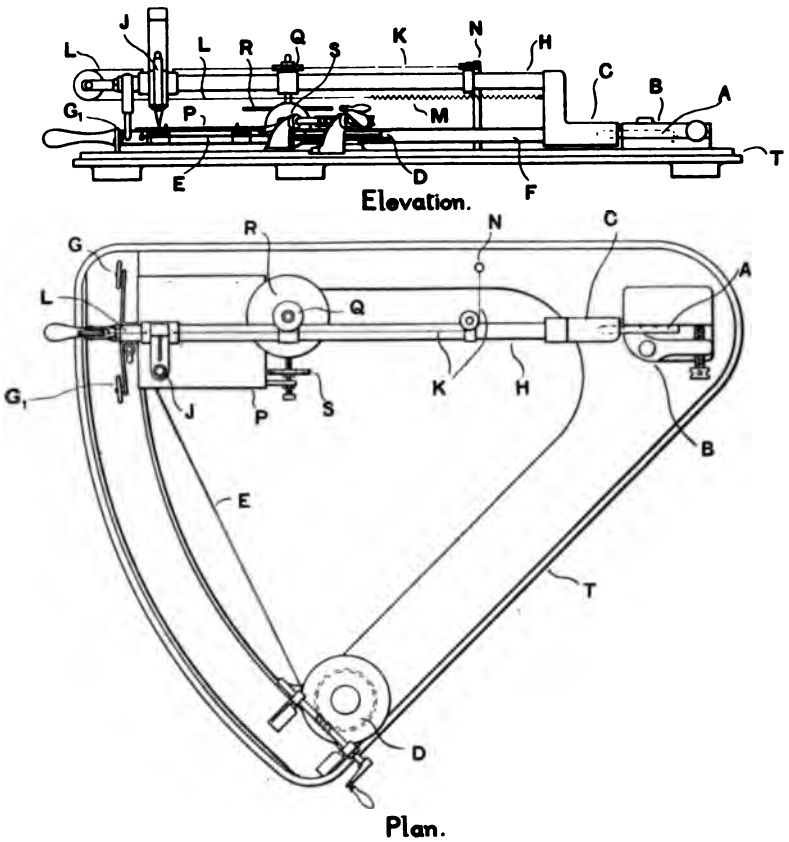

FIG. 213.—Diagram of the Humphrey autographic notched bar testing machine.

cent. of that given by an impact test (in two or three cases the energies obtained by the two methods are approximately equal), and he attributes this difference to energy dissipated in the pendulum testing machine. The striking velocity in Philpot's impact tests did not exceed 3·5 metres per second and his conclusions only hold up to that value.

Philpot for his slow bending tests uses an ordinary Brinell machine and measures the deflections of the specimen for different loads by means of a microscope. The results are plotted and the area of the curve is integrated in order to obtain the total energy absorbed.

The Humphrey Autographic Notched Bar Testing Machine, made by the Foster Instrument Company of Letchworth, is devised to carry out this class of test rapidly and conveniently and in a manner giving the maximum information as to the material in a minimum time. It is illustrated diagrammatically in Fig. 213 and photographically in Fig. 214.

The test-piece (A) is gripped in the vice (B) so that the jaws of the vice are in line with the notch in the test-piece. The

FIG. 214.—The Humphrey autographic notched bar testing machine.

socket (C) is attached on the projecting end of the test-piece and is a reasonably close fit thereon. A bending stress is applied to the test-piece by means of the winch (D) and the wire (E) which is attached to the outer end of the spring bar (F). The inner end of the spring bar is firmly fixed to the socket (C). The outer end of the spring bar is supported by two rollers (G and G1). The socket (C) carries also a rigid bar (H).

The deflection of the spring bar (F) is a measure of the bending moment applied to the test-piece. Since the rigid bar (H) is not subjected to any bending moment it will move through the same angle as the socket (C), and this movement will therefore be a measure of the bending of the test-piece. The pen (J) slides upon the rigid bar (H), its position being determined by

the thin wires or cords (K and L), which are kept taut by a light spring (M). One end of the wire (K) is attached to a post (N) so that as the rigid bar (H) moves in consequence of the bending of the test-piece the wire (K) will draw the pen to the right. The point of the pen marks upon a calibrated chart (P) carried on the spring bar (F), therefore, if the test-piece offers no resistance whatever to bending force, the pen would draw a horizontal line on the chart, the length of which is proportional to the angle through which the test-piece is bent. As, however, the test-piece does offer resistance to bending there will be a resulting movement between the spring bar (F) and the rigid bar (H).

The pen, therefore, draws a diagram showing the relation between bending moment applied and angle of bending throughout the duration of the test. The total energy absorbed in the breaking of the test-piece can be obtained from the area of this diagram.

The machine can also be fitted with an integrating device so that the energy absorbed can be read directly from the machine. This device is shown in Figs. 213, 214. The wire (K) passes round a pulley (Q). The pulley (Q) is attached to a spindle having at its lower end a friction disc (R) so that the bending of the test-piece which results in the movement of the pen to the right also results in a proportionate rotation of the friction disc (R).

The under face of this disc rests upon the edge of the friction wheel, not shown. The spindle of the friction wheel is carried with the chart plate upon the spring bar (F). When the bending moment is zero the friction wheel is at the centre of the friction disc, but as bending moment is applied and there is relative movement between the spring bar (F) and the rigid bar (H), the friction wheel travels towards the circumference of the friction disc, and is consequently rotated. The rotation will be proportional to the product of the bending moment applied and the angle of bending of the test-piece, and this device will therefore integrate the total energy absorbed in breaking the test-piece. Mounted upon the outer end of the spindle which carries the friction wheel is an index disc (S) which can be calibrated to read direct in foot-lbs.

§ 207. **Tests on Specimens of Different Sizes.**—A trustworthy relation has not been found between the energy to fracture in test-pieces of different sizes, there is, however, evidence that it is probably different for different materials. This

is shown from an examination of the results in Table LXIX, which gives the results of notched bar impact tests on two different steels with geometrically similar test-pieces.

TABLE LXIX.

TESTS ON GEOMETRICALLY SIMILAR SPECIMENS.

Dimensions of Specimen in Mm.*	Energy to Fracture.					
	Steel A.			Steel B.		
	Kg.M.	Kg.M./Cm².	Kg.M./Cm³.	Kg.M.	Kg.M./Cm².	Kg.M./Cm³.
10 × 10 × 53·33	4·77	5·96	0·89	1·28	1·60	0·24
30 × 30 × 160	60	8·33	0·42	36·3	5·04	0·25
63 × 63 × 336	296	9·32	0·22	197	6·20	0·15

* The notch for the 10 × 10 test-piece was a 45° V, 0·25 mm. root radius and 2 mm. deep. The notches for the larger test-pieces were geometrically similar.

It will be noted that :—

(1) The energy absorbed is not proportional to either the square or the cube of the dimensions of the test-piece.

(2) With the 10 × 10 mm. test-piece, steel A takes $3\frac{3}{4}$ times the energy that steel B does, but with the 63 × 63 mm. test-pieces it is only $1\frac{1}{2}$ times.

There is apparently a scale speed factor in the law of resistance of notched specimens to sudden shock which appears to be of extreme complexity.

Full particulars of an extensive series of tests on this subject are given in a recent paper by Stanton and Batson.[10]

Saniter suggests that one of the difficulties in obtaining a trustworthy relation with size of test-piece is the deformation of the notched sides of the specimen. He suggests that the notched bar test-piece should be notched on three sides the hammer striking on the unnotched surface. The test-piece will then be 14 × 10 × 60 mm., with the 45° V Izod notch on each of three faces making the cross-sectional dimensions at the bottom of the notch 10 × 8 as in the present standard test-piece.

§ 208. **Tests on Unnotched Bars.**—With geometrically similar unnotched test-bars, either beams or tensile test-pieces, the energy absorbed in fracture for the same material is proportional to the volume of the test-piece.

Hatt,[11] in 1904, as the result of some experiments in dynamic

tension, came to the conclusion that, for steels, there is little difference in the total elongation and the unit work in fracture whether the fracture is brought about in 10 minutes or 0·01 second. Stanton and Bairstow,[4] in 1908, and Delikhow,[12] in 1909 (using a drop-hammer type of machine), have also shown that the tensile impact test (i.e. dynamic tensile test) gives numerical values which agree with the results of the static tensile test.

Blount, Kirkaldy and Sankey,[13] in the summary to their paper on steel testing methods, say that "the impact tensile test gives the ductility in the same terms as the static tensile test, namely, elongation and contraction of area, but always with higher numerical values. The breaking stress of the material can be inferred, but must be reduced by a factor in order to obtain the same numerical value as given by the static test: also it only gives the breaking stress. The energy absorbed per cubic inch does not vary greatly with the various types of steel; it is approximately 50 per cent. more than that obtained by the static tensile test, and is also no definite criterion of the type of the steel; at any rate, of normal steels containing a small proportion of phosphorus. From the experiments referred to by Breuil[14] it would appear that steels containing an undue proportion of phosphorus give a much smaller energy per cubic inch with impact tensile tests."

§ 209. **Tests Under Repeated Bending Impact.**—In 1908 Stanton[4] carried out extensive investigations on the method of testing by repeated impact and devised a machine to reproduce stress conditions which are met with in certain machine parts in actual use, where the effect of alternating blows is produced on the material at positions where there is a rapid reduction of cross section.

The test-bar, 0·500 inch diameter and 6·5 inch long, is supported on knife edges 4½ inches apart. The test-piece has a groove turned round the centre of the span 0·05 inch deep, so that the effective diameter at the bottom of the groove is 0·400 inch. The groove is in the form of a V whose angle is 55° and root radius 0·01 inch. The test-piece is fixed in the machine where it receives blows at the rate of about ninety per minute from a hammer whose weight is 4·71 lbs. and of which the height of fall is adjustable.

Between each blow the bar is turned through 180° and the test is continued until failure of the test-bar. The number of blows to cause failure is recorded by a counter.

A series of tests is usually made on each material with varying energies of blow and, by plotting the energies of blow as ordinates and the number of blows to fracture as abscissæ, a curve is obtained from which useful information as to both the impact strength and fatigue strength of the material can be obtained. In Stanton's original paper it is stated that when the number of blows is less than 500 the results approximate to those of the single blow impact test and that, when the number of blows for fracture exceeds 100,000, the results are in the order of the fatigue ranges of the materials as determined in a Wöhler test. The interpretation of the results which has commonly been made during the late war, with a height of fall which produces fracture after about 4000 to 6000 blows, is almost impossible.

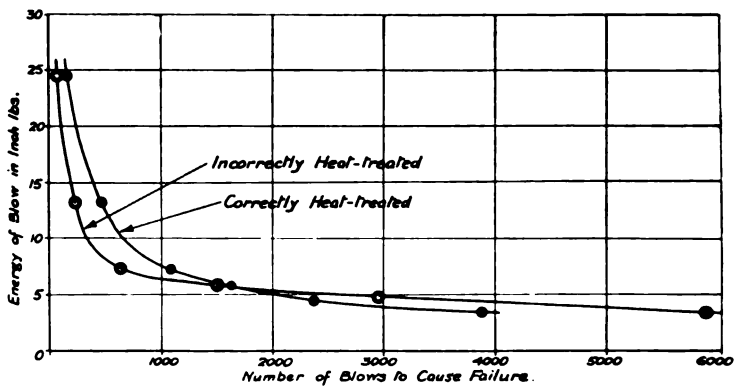

FIG. 215.—Repeated impact tests (Stanton's method) on correctly and incorrectly heat-treated boiler plate.

The results from tests on steel correctly and incorrectly heat treated are given in Table LXX and plotted in Fig. 215.

It will be noted that the incorrectly heat-treated bars are considerably weaker as regards notched bar impact but slightly stronger under fatigue.

The test-bar previously described is the one adopted by Stanton for his research and has a notch very similar to the standard Izod notch which is easily reproduced. A notch 0·05 inch wide and 0·05 inch deep with parallel sides and practically sharp corners has been sometimes used in conjunction with this test.

The Eden-Foster machine, manufactured by the Foster In-

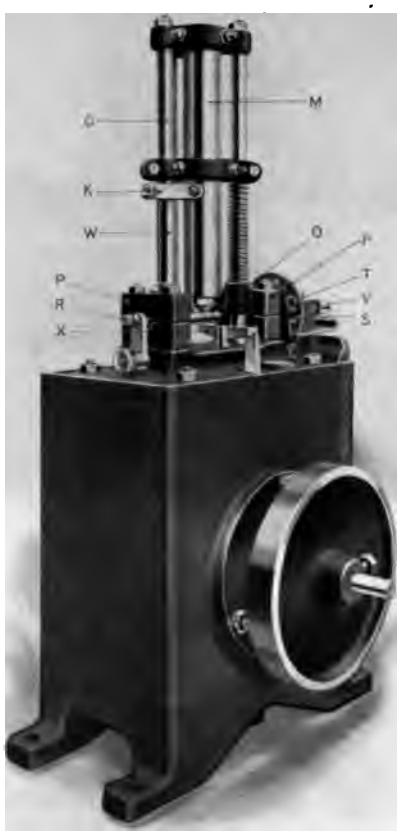

FIG. 216.—Eden-Foster repeated bending impact machine.
[*To face p.* 321.

strument Company, Letchworth, is a close copy of Stanton's original machine and embodies its principal features.

TABLE LXX.

REPEATED BENDING IMPACT TESTS ON BOILER PLATE CORRECTLY AND INCORRECTLY HEAT TREATED.

Energy of Blow. Inch-lbs.	Number of Blows to Cause Failure.	
	Material Correctly Heat Treated.	Material Incorrectly Heat Treated.
3·53	3886	5871
4·71	2356	2913
5·89	1636	1450
7·35	1043	629
13·32	474	259
24·46	155	61

The illustration (Fig. 216) gives a general idea of the external appearance of the machine. The main spindle projects through the side of the box casting and is driven by an electric motor with suitable gear or worm reduction. About 0·1 horse-power is required to drive the apparatus.

The main spindle carries a dog clutch driving a cam, which has a roller bearing on its upper surface and attached to the lower end of a rod. Fixed on the rod is an arm which engages with the lower face of the hammer (M), thus when the rod rises by rotation of the cam the hammer (M) is lifted. The guides for the hammer consist of two sets of three point screws carried by two castings attached to the standard (G) and its fellow on the opposite side.

Mounted on the standard (G) is a sleeve (W), free to rotate about the standard but normally held in a fixed position by a spring. Clamped on the sleeve (W) is an adjustable catch (K). As soon as the arm has lifted the hammer sufficiently, the spring causes a partial rotation of the sleeve (W) so that, when the arm again descends, the hammer is held by the catch (K). The further descent of the arm brings its lower inclined face in engagement with a roller attached to the sleeve (W), in such a manner that the catch (K) releases the hammer (M) allowing it to fall upon the test-piece (O). The hammer (M) is furnished with a hardened tool steel tup. Two hammers are provided to allow for a wide range of tests, the weights being 5 and 2 lbs. respectively. The height of drop,

which depends upon the position of the adjustable catch (K) on the sleeve (W), can be varied from 1 to 4¼ inches.

The test-piece is carried by two hardened steel bushes in the plummer blocks (PP). It is rotated through 180° between successive blows, the rotation being arranged so that it begins and ends entirely between the successive blows.

The revolutions of the test-piece are recorded by a counter (V) and the number of blows is found by multiplying the counter record by two. When the test-piece breaks, it comes in contact with an arm (X) and thereby trips the clutch and stops the machine.

The test-piece is driven, through a universal joint, by the chain (S), freewheel and clutch (T). One end of the chain is attached to the roller, at the lower end of the rod which bears on the cam and the other end carries a suitably guided weight.

All the gear is fixed to the casting which forms the cover of the lower tank casting. The latter is partially filled with oil for lubrication of the surfaces.

REFERENCES FOR CHAPTER XIX.

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[4] Stanton and Bairstow, "Resistance of Materials to Impact," "Inst. Mech. Eng. Proc.," Nov. 20th, 1908, and "Revue de Metall.," March, 1909.

[5] Harbord, "Different Methods of Impact Testing on Notched Bars," "Inst. Mech. Eng. Proc.," Oct.-Dec., 1908.

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[7] Philpot, "Some Experiments on Notched Bars," "Inst. of Automobile Eng. Proc.," April, 1918.

[8] Thomas, "Charpy Impact Tests on Heat-treated Steels," "Amer. Soc. Test. Mat. Proc.," 1915, Vol. XV, p. 75.

[9] Dix, "Single Blow Notched Bar Impact Test as used in the American Industry," "Amer. Soc. Test. Mat. Proc.," 1919, Vol. XIX, Pt. II, p. 721.

[10] Stanton and Batson, "The Characteristics of the Notched Bar Impact Test," "Inst. Civil Eng. Proc.," Nov., 1920.

[11] Hatt, "Tensile Impact Tests of Metals," "Amer. Soc. Test. Mat. Proc.," 1904, Vol. IV, p. 282.

[12] Delikhow, "Note on the Rupture of Normal Cylindrical Test Samples by Longitudinal Impact," "Inter. Assoc. Test. Mat. Proc.," 1909.

[13] Blount, Kirkaldy and Sankey, "Comparison of the Tensile, Impact Tensile, and Repeated Bending Methods of Testing Steel," "Inst. Mech. Eng. Proc.," May 27th, 1910.

[14] Breuil, "Revue de Mécanique," 1908, p. 537.

CHAPTER XX.

EFFECT OF TEMPERATURE ON THE MECHANICAL PROPERTIES OF MATERIALS.

§ 210. MANY parts of machinery work at temperatures considerably above or below the normal and it is essential for the purpose of economy and safety in design that the more important effects of temperature on the mechanical properties of materials should be well understood.

§ 211. **Tensile Strength, Elongation, etc., at High Temperatures.**—Strength tests at high temperatures have been carried out since the early part of the nineteenth century.

In 1820 Tremery and Proirier-Saint-Brice[1] showed that, although the tensile strength of hammered wrought iron was 27·6 tons per square inch at air temperature, it fell to 5·0 tons per square inch at red heat. Fairbairn,[2] in this country, carried out a series of experiments in 1856, and numerous other investigations have been made since that time confirming and extending the work of the earlier experimenters.

§ 212. **Testing Apparatus.**—The oldest method used for testing at temperatures above that of the air was that of heating the test-piece in a furnace, transferring it to the testing machine, and conducting the test very quickly in air. The values obtained by that method were very unreliable and in recent tests the samples have been immersed in a hot bath for the whole duration of the test.

The medium used in the hot bath can either be a liquid or gas but it is essential that the heating medium should neither attack nor alloy with the test-piece. Suitable materials for liquid baths are given in Table LXXI.

Air is nearly always used for the gas bath but it causes oxidation of the test sample and for special cases the test may be carried out in vacuo,[3] nitrogen,[4] or carbon dioxide.[5] Rudeloff[6] made use of baths of steam (up to 100° C.), naphthalene vapour (200° C.) and naphthylamine vapour (300° C.).

TABLE LXXI.

Material.	Temperature Used in °C.
Water	up to 100
Paraffin	,, 200
Mineral oil	,, 350
Nitrate of potassium and nitrate of sodium	350-600
Lead and tin	300-400

The heating of the bath is carried out in several ways :—

(1) By gas jets arranged underneath the test-piece, which is held horizontal. This method was adopted by Unwin [7] for a liquid bath and by Charpy [8] for an air bath.

(2) By gas jets above a horizontal test-piece, adopted by Le Chatelier.[9]

(3) By gas jets at the sides. This is used in conjunction with a vertical testing machine by Martens [10] and Bach.[11]

(4) Steam heating coils are used for tests on 50-feet lengths of copper wire, up to temperatures of 60° C., carried out at the National Physical Laboratory.[12]

(5) Electric heating coils are used by Stribeck,[13] and Hopkinson and Rogers.[14]

For general convenience the last method is to be preferred. Two electric furnaces, successfully used at the National Physical Laboratory, are given in Figs. 217 and 218. They are both used in connection with a vertical testing machine.

A platinum furnace for temperatures up to 1200° C. is shown in Fig. 217. The heater (*a*) consists of a platinum strip, 0·75 × 0·0007 inch, wound on a fire-clay cylinder (outside diameter 2·25 inches, thickness 0·187 inch and 13⅞ inches long) with a pitch of 1 inch. The ends of the strip are clamped in position on the cylinder by metal clips (D). A steel case (B) (about 8 inches diameter and $\frac{1}{16}$ inch thick) surrounds the heater, and the space between the two is packed with asbestos and magnesia wool. The whole is clamped between two end plates (C_1 and C_2), on one of which two insulated terminals are fixed, these are connected to the two ends of the platinum heating coil. The furnace, which is slung from the top shackle of the testing machine, takes a current of 15 amperes at 105 volts.

Fig. 218 shows the 600° C. furnace. With this furnace the heater is formed with ni-chrome wire wound on to a brass tube (A) (2⅜ inches diameter and 15 inches long). The tube is bound

with mica, before winding the wire, in order to insulate it, and over the wire a binding of asbestos string is placed so as to keep the former in position when it expands on rise of temperature.

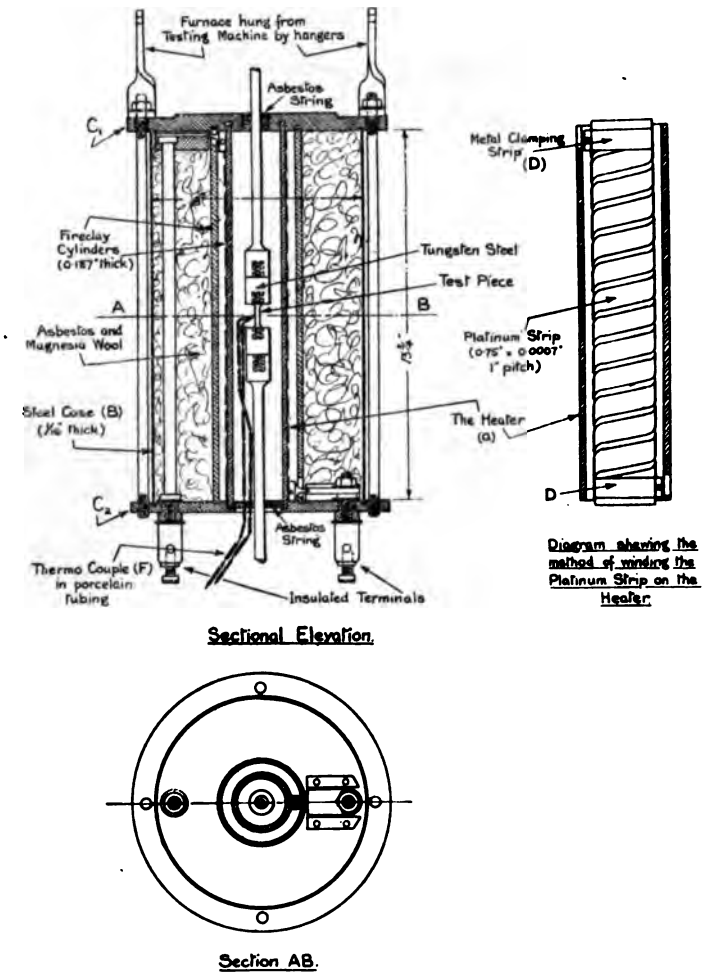


FIG. 217.—Platinum high temperature furnace for tensile tests.

The heater is surrounded by a steel case (B), 7 inches diameter, and the space between the two is filled with asbestos wool. Two steel plates (C_1 and C_2) are bolted together, clamping the heater and outer case between them, and are arranged to connect the

furnace to the frame of the testing machine at E_1 and E_2. Th

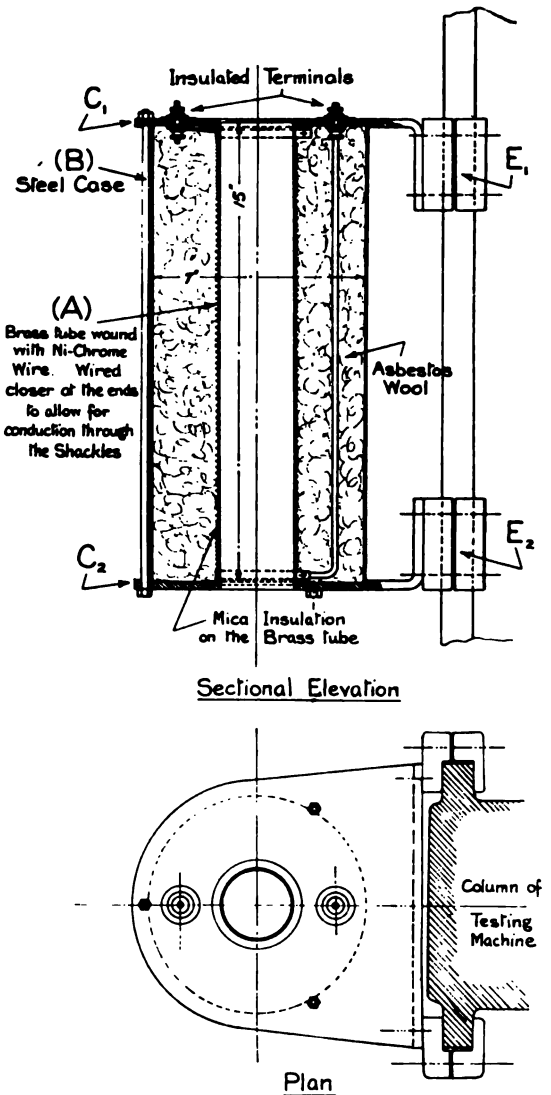


FIG. 218.—Furnace for tensile tests up to 600° C.

ends of the heating coil are connected to two insulated terminal: on the top plate. No. 18 ni-chrome wire, having a carrying

capacity of 11 amperes at 500° C. is used for the heater. The wire is coiled closer at the ends in order to allow for the conduction of heat through the shackles and give uniform heating over the central 3 to 4 inches of the furnace.

In another furnace of the same type the conduction of heat through the shackles is equalised by having the main heating coil wound at constant pitch throughout its length and supplementing this by two further coils, one wound at each end of the furnace. These coils are wound over the main coil, mica insulation being inserted, and are connected to separate circuits.

§ 213. **Arrangement of Testing Machine Grips and Rate of Loading.**—It is important that the size of test-piece, form of grips and length of furnace should be carefully proportioned to obtain uniform heating of the test-piece. It is found that either high chromium, low carbon or high tungsten, high carbon steels (i.e. 13 per cent. chromium, 0·35 per cent. carbon or 18 per cent. tungsten, 0·60 per cent. carbon) give the most satisfactory holders for tests at over 600° C., as they combine a fairly high tensile strength with freedom from scaling. Of the two steels the former scales very little while the latter, although it scales a little more, has a slightly higher tensile strength at high temperatures.

Uniformity of speed in loading is an important condition for strictly comparable results. As the speed of loading increases greater strength values are obtained. Le Chatelier found that with hard drawn copper wire tested at 250° C., the ultimate breaking strength increased from 11·4 to 21·6 tons per square inch as the duration of the test decreased from 1800 seconds to 20 seconds. Both Le Chatelier and Stribeck have shown that the elongation of copper diminishes with reduction in the speed of loading.

§ 214. **Temperature Measurement for Strength Tests.**—With liquid baths sufficient accuracy can usually be obtained by taking the temperature of the liquid, but it is essential that the test should not be carried out until uniformity of temperature is attained.

With an air bath there is incomplete conduction of the heat between the surrounding air and the test-piece and it is necessary that the temperature of the sample should be directly measured. This is most conveniently carried out by means of a thermo-electric pyrometer, which can either be placed in a hole drilled down the test-piece, as was done by Bregowsky and Spring,[15] or laid close against the sample and bound to it with asbestos string.

In a recent furnace,[16] a spring on the outside of the casing

forces a porcelain rod through a hole in the furnace and on to the thermo-couple holding the point of the couple against the test-piece.

The thermo-electric pyrometer consists of three parts, viz. :—

(1) The thermo-couple which is attached to the test-piece and is at the same temperature.

(2) The indicator from which the temperatures are observed.

(3) Leads connecting the thermo-couple to the indicator.

The thermo-couple consists of two wires (A and B) of different composition. The ends of A and B are joined together and form a circuit. One junction is maintained at a known temperature, usually zero, while the other is placed against the material whose temperature is to be ascertained. The difference in temperature between these ends sets up an electromotive force which is proportional to the temperature difference. This E.M.F. is measured and by means of a calibration gives the temperature. The cold junction is usually placed in ice in order to insure a constant temperature. A thermos flask is a convenient receptacle for the ice and cold junction.

Various combinations of metals are used for thermo-couples according to the maximum temperature for which they are to be used :—

(*a*) Base metal thermo-couples.

Iron-constantan (wires) thermo-couples for temperatures up to 600° C.

Iron-constantan (rods) thermo-couples for temperatures up to 800° C.

(*b*) Rare metal couples.

Platinum-platinum and 10 per cent. rhodium } for temperatures
Platinum-platinum and 10 per cent. iridium } up to 1400° C.

It is essential, for temperatures above 800° C., that the couple should be protected by quartz or porcelain tubes. A thermo-couple placed in small porcelain tubing is seen at F (Fig. 217).

The indicator is usually a sensitive moving coil galvanometer of high internal electrical resistance, having the scale marked in temperature readings which depends upon the type of thermo-couple employed. It is generally an advantage to also have the instrument provided with a scale giving its readings in millivolts.

Complete thermo-electric pyrometer outfits are supplied by various firms of instrument makers. Fig. 219 shows the type of indicator which the authors have found most suitable for ordinary high temperature test work. It is supplied by the Cambridge & Paul Instrument Company.

§ 215. **Determination of Limit of Proportionality and Yield Point at High Temperature.**—In the majority of high temperature furnaces the test-piece is not visible during the test, so that the yield point, if one exists, cannot be obtained by noting the extension by a pair of dividers, and the attachment of an extensometer is more difficult than with tests at air temperature.

In 1890 Martens [17] adapted his mirror extensometer for high temperature work. The test-piece *tt* (Fig. 220 (*a*)) was turned down in the centre at *cd*. The extensometer clips were attached at *b* on the lower enlarged end and were carried out of the furnace

FIG. 219.—Indicator for high temperature measurement.

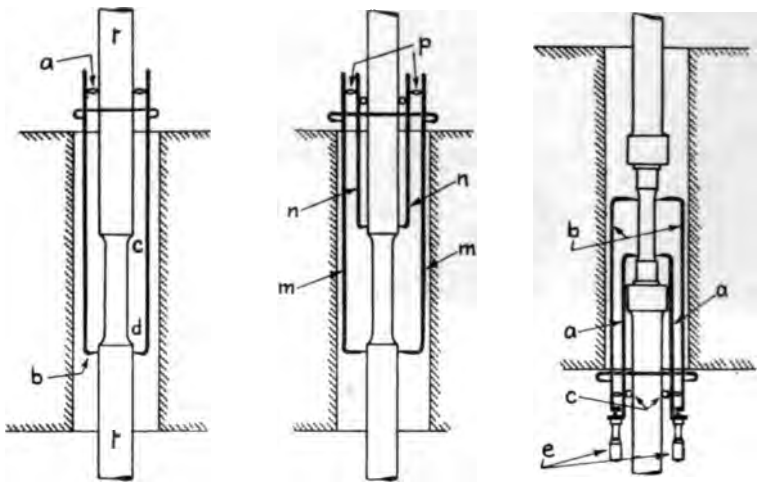
for attachment of the measuring rhombs at *a*. The extension was therefore measured on the length *ab* and correction was made for the extension of the enlarged ends in order to obtain the extension of the gauge length *cd*.

Rudeloff,[18] in 1895, slightly modified Martens' arrangement and used two pairs of clips, *m* and *n* (Fig. 220 (*b*)), with the mirror rhombs (*p*) between them. Here, again, the true elongation has to be obtained by calculation, the length of the thick part, however, is small and as the whole of the measured length is in the furnace the observations are uninfluenced by variations of temperature.

Lee and Crowther,[19] in 1914, adapted Rudeloff's arrangement

of clips to a horizontal testing machine, they, however, attached them to the reduced part of the test-piece.

In Figs. 220 (*c*) and 221 is shown the high temperature extensometer which is proving very useful at the National Physical Laboratory. This is a combination of the best features of both Rudeloff and Lee's extensometers with the addition of two micrometers for measuring extensions beyond the elastic limit. The clips (*aa* and *bb*) are attached to the reduced part of the test-piece by C springs and protrude from the furnace. The inner clips (*aa*) are guided on flats on the test-piece holders by small rollers (*cc*). Mirrors and rhombs are placed between the



(a) Martens Arrangement. (b) Rudeloff's Arrangement. (c) N.P.L. Arrangement.

FIG. 220.—Diagrams of high temperature extensometers.

clips and the whole is clamped together by a special spring attached to notches on the outer clip.

Extension of the test-piece causes relative movement of the clips (*aa* and *bb*) and therefore rotation of the mirror rhombs which is measured in the usual way by a telescope and scale The relative movement of the clips is also measured by two micrometers (*e*) attached to the inner clips and working against the outer ones.

Curves for tests on phosphor-bronze with this instrument are shown in Figs. 222 and 223. Fig. 222 gives the elastic line and limit of proportionality at temperatures of 20°, 120°, and 288° C.

plotted from results with the rhombs and mirrors, and Fig. 223

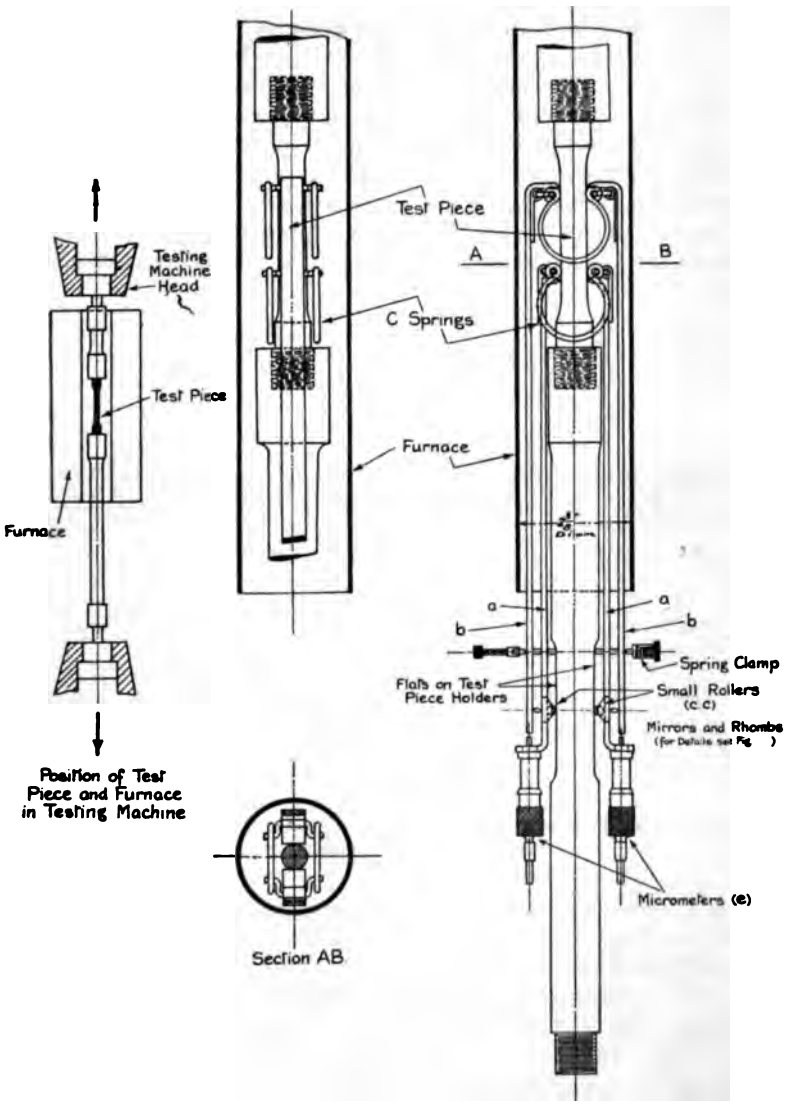


FIG. 221.—National Physical Laboratory high temperature extensometer.

shows the full stress-strain curves at temperatures of 20°, 120°, 205°, and 288° C., obtained by using the micrometers.

An extensometer of the mirror type has recently been constructed by H. Edert[20] for tests up to temperatures of 950° C. The levers, clips and knife edges are made of chrome nickel steel which will stand temperatures of 1000° C. The knife edges are mounted above the furnace and are kept cool by a current of air from two nozzles of 40 × 1 mm. mouth gap.

§ 216. **Results of Tensile Tests.**—(i) *Iron and Carbon Steels.*—Fairbairn in 1856, showed that iron possesses a maximum resistance to fracture at 250° C. and this has frequently been verified for iron and steel. It has also been shown that this maximum resistance is preceded by a minimum which occurs at about 120° C.

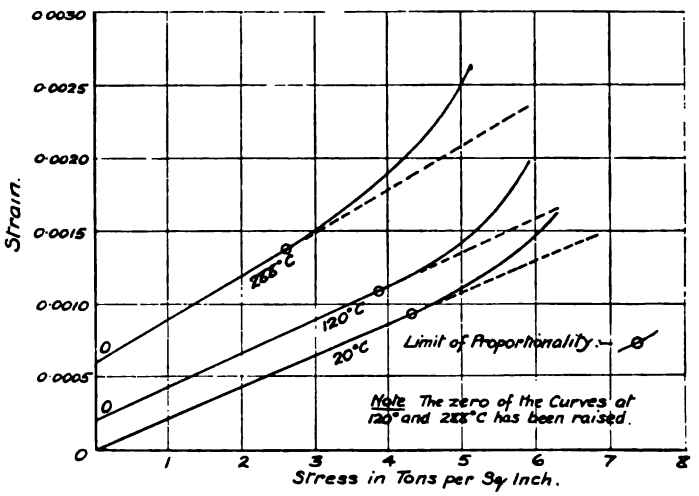


FIG. 222.—High temperature tensile tests on phosphor-bronze, giving the elastic line and limit of proportionality.

An extensive series of tests were carried out on iron and steel at the Watertown Arsenal[21] in 1888 from which the following conclusions can be drawn:—

(1) The change in the ultimate strength is very small up to about 150° C. There is evidence of a slight reduction at from 100° to 120° C., and after 150° C. there is an increase until at 250° C. a maximum is reached which is from 10 to 15 per cent. higher than the normal. From 250° to 950° C. there is a continuous fall in strength which at the latter temperature gives a reduction in strength of 80 to 85 per cent. of the normal.

(2) The elastic limit decreases with increasing temperature.

Up to 350° C. this decrease is directly proportional to increase in temperature, so that at 350° C. the elastic limit is about 70 to 75 per cent. of that at normal temperature.

(3) With cast iron the ultimate strength is approximately constant up to 500° C. after which it falls until at 950° C. it is about 20 per cent. of the normal value.

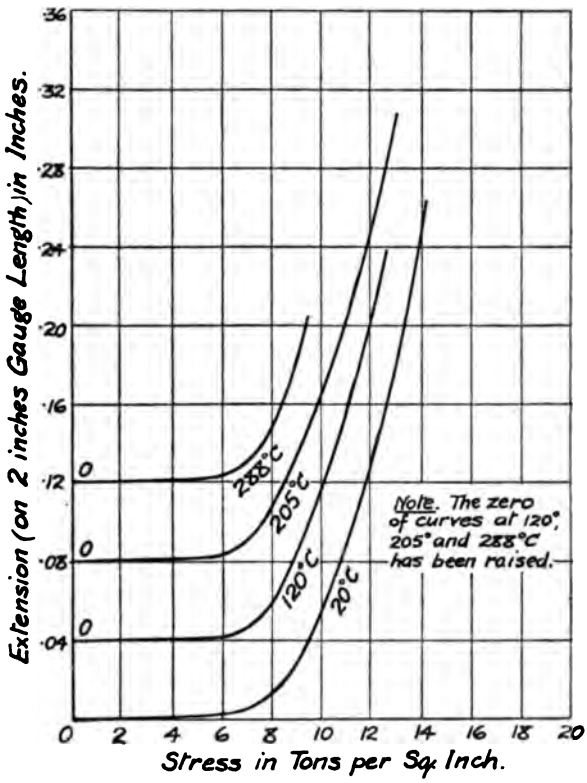


FIG. 223.—High temperature tensile tests on phosphor-bronze (complete curves).

Martens,[10] in 1890, published an elaborate series of tests on the strength of steel at temperatures up to 600° C. and included a determination of the limit of proportionality. He used a paraffin bath for temperatures up to 200° C., a bath of lead and tin for temperatures up to 600° C. and for low temperatures a mixture of three parts by weight of ice and one part of salt. Temperatures up to 400° C. were measured with a mercurial

thermometer and for higher temperatures an air thermometer was employed.

Tests by Lea and Crowther[19] show that the modulus of elasticity of mild steel varies from $29{\cdot}6 \times 10^6$ lbs. per square inch at normal temperature to $12{\cdot}8 \times 10^6$ at 600° C. They also found that the ultimate stress was a maximum at 250° C. but that the stress obtained by dividing the breaking load by the area at fracture was a minimum at that temperature. The figures given in Table LXXII have been taken from their plotted results.

TABLE LXXII.

TENSILE TESTS ON MILD STEEL AT VARYING TEMPERATURES.

Temperature °C.	Modulus of Elasticity. Lbs. per Sq. In.	Yield Stress. Tons per Sq. In.	Ultimate Stress. Tons per Sq. In.	Reduction of Area. Per Cent.
20	$29{\cdot}6 \times 10^6$	21·4	28·7	57
110	$29{\cdot}3 \times 10^6$	19·4	29·2	—
240	$28{\cdot}3 \times 10^6$	16·6	39·0	65
310	$27{\cdot}6 \times 10^6$	16·3	37·9	62
445	$23{\cdot}3 \times 10^6$	15·4	25·7	32
520	$17{\cdot}7 \times 10^6$	12·5	17·3	15
570	$14{\cdot}8 \times 10^6$	9·7	12·1	4
600	$12{\cdot}8 \times 10^6$	—	—	—

Some tests have very recently been carried out in America[16] using a furnace similar to the 600° C. furnace (Fig. 218) described in § 212. The results are summarised as follows:—

"There is no one temperature at which all steels show a decided change in physical properties; this point varies in steels of different composition or treatment. The maximum tensile strength of rolled carbon steel, annealed and forged 3¼ per cent. nickel steel annealed occurs at between 315° C. and 345° C.

"The maximum tensile strength usually occurs at a higher temperature than the minimum ductility.

"The majority of tensile test curves (especially heat-treated steels) drop sharply as the temperature exceeds 425° C."

(ii) *Alloy Steels.*—The behaviour of special alloy steels at high temperature has been studied by Aitchison.[22] A synopsis of results of tensile tests, most of which were made at the National Physical Laboratory, is given in Table LXXIII, these show that the tungsten steels with high percentages of carbon (i.e. about 0·6 per cent.) have the greatest tensile strength at

high temperatures. This strength is nearly equalled by the high chromium steels also containing a high percentage of carbon.

With high chromium and high tungsten steels the percentage of carbon seems to play an important part in their strength at high temperatures. Thus, with the 11 per cent. chromium steel, reducing the carbon content from 1·0 to 0·4 per cent. reduces the tensile strength at 900° C. from 7·5 to 4·8 tons per square inch, while a reduction of the chromium content from 11 per cent. to 6·3 per cent. with the carbon content at 1 per cent. has no effect on the tensile strength at that temperature.

When the temperature exceeds 600° C. the strength of alloy steels falls off rapidly, this is particularly noticeable with nickel chrome steels and nickel steels between which there is very little difference at high temperature.

TABLE LXXIII.

Steel.	Ultimate Strength in Tons per Sq. In. at Temperature °C.							
	15.	650.	700.	750.	800.	850.	900.	950.
17 per cent. tungsten, 0·65 per cent. carbon	58	25	17·7	13	10·3	11·1	8·8	6·6
16 " " 0·45 " "	45	—	15·5	—	—	—	6·3	—
14 " " 0·70 " "	51	20	15·9	10	7·0	10·0	7·6	—
12 " " 0·45 " "	48	—	14·7	—	7·1	9·6	7·4	—
11 per cent. chromium, 0·40 " "	43	14	12·1	8	6·6	—	4·8	4·0
11 " " 1·0 " "	67	—	15·1	10	8·5	9·6	7·5	6·5
6·3 " " 0·5 " "	66	—	17·0	—	—	—	7·0	—
6·3 " " 1·1 " "	78	—	18·5	—	—	—	7·5	—
3 per cent. nickel, 0·3 " "	50	—	9·4	—	—	—	3·9	—
3 " " 0·6 " "	—	—	11·5	—	—	—	4·5	—
3 per cent. chromium, 0·35 " "	—	—	8·5	—	—	—	4·2	—
3 " " 0·7 " "	—	—	11·7	—	—	—	4·9	—
Ordinary nickel chromium . . .	55	16	10·5	8	7·0	5·1	4·5	3·0

(iii) *Alloys.*—The use of fittings under superheated steam involves temperatures up to 400° C. and the study of brasses, bronzes, etc., up to these temperatures has been undertaken by numerous investigators. Unwin[23] in 1889 communicated a report to the British Association on tensile tests of Delta metal, gunmetal, muntz metal, copper, brass, phosphor-bronze and aluminium bronze at temperatures up to 350° C.

Rudeloff,[24] Bregowsky and Spring,[15] Dewrance,[25] and Law,[26] have also carried out a great deal of work on this subject.

The tensile strength at high temperatures of aluminium

copper, aluminium copper manganese, and aluminium zinc alloys are given in the reports of the Alloy Research Committee.[27]

The variations, with temperature, in the properties of alloys are fairly regular; there is a fall in the tensile strength as the temperature rises with changes of curvature and sometimes humps in the temperature—ultimate stress curve. Rolled monel metal, an alloy of 70 per cent. nickel with 30 per cent. copper, exhibits high strength and ductility at temperatures up to 550° C.

Tests at the National Physical Laboratory[12] on hard drawn copper and bronze wire show that between − 20° C. and +60° C. a rise of 1° C. corresponds to a decrease of 0·1 per cent. of the breaking load and an increase of 0·3 per cent. in the total extension at 15° C. There is also a slight alteration of the modulus of elasticity with temperatures met with under climatic conditions. Tests by F. C. Lea[28] on Delta metal, manganese bronze, gunmetal and nicro-copper show that the effect of temperature on the modulus of elasticity of these alloys is very noticeable. The results are summarised in Table LXXIV.

TABLE LXXIV.

TESTS AT VARYING TEMPERATURES CARRIED OUT BY F. C. LEA.

Material.	Temperature. °C.	Limit of Proportionality. Tons per Sq. In.	Ultimate Stress. Tons per Sq. In.	Modulus of Elasticity in Lbs. per Sq. In.
Delta metal . .	15	4·6	32·65	15·4 × 10^6
	250	2·8	28·0	14·1 × 10^6
	350	0·8	18·6	8·7 × 10^6
	450	less than 0·2	7·32	—
Manganese bronze .	15	6·3	32·5	15·2 × 10^6
	250	4·8	23·15	13·7 × 10^6
	350	below 0·4	12·6	—
	450	below 0·4	4·08	—
Gunmetal . . .	15	3·2	15·82	12·9 × 10^6
	250	2·8	16·06	13·0 × 10^6
	350	2·2	10·27	11·2 × 10^6
	450	1·6	5·2	8·7 × 10^6
Nicro-copper . .	15	4·0	16·59	18·3 × 10^6
	250	2·4	12·98	17·2 × 10^6
	350	3·4	11·4	15·5 × 10^6
	450	2·0	11·3	11·5 × 10^6

§ 217. **Tensile Tests at Low Temperatures.**—These tests are usually carried out by surrounding the test-piece with a bath containing a cooling substance such as :—

Ice	for temperatures down to			0° C.
Ice and freezing salt . .	„	„	„	− 20° C.
Frozen mercury . .	„	„	„	− 40° C.
Solid carbon dioxide powder	„	„	„	− 80° C.
Liquid air	„	„	„	− 185° C.

It is essential that the bath should be surrounded with a casing containing down packing or asbestos wool in order to obtain a uniform temperature.

Rudeloff, in 1895, found that iron and steel gave increased yield stress and ultimate stress as the temperature was lowered, while the extension was generally decreased by cooling. Tests made at Watertown Arsenal [29] gave an increase of about 50 per cent. in the yield stress and 35 per cent. in the ultimate stress, over the normal values, when tested at − 185° C., but the extension decreased by 63 per cent.

Cast aluminium light alloys show an increase, over the normal, in ultimate strength of 9 per cent. at − 80° C. and 27 per cent. at − 185° C.

§ 218. **Notched Bar Tests at Varying Temperatures.**—Charpy [30] has shown that, with steel, the work absorbed in the fracture of a notched bar test-piece rises as the temperature is increased and reaches a maximum at about 150° C., it then decreases and passes through a minimum between 400° C. and 500° C. and rises again until red heat is reached.

This work was confirmed by Guillet and Revillon who gave the temperatures of maximum and minimum resistance to shock as 200° C. and 475° C., they say that there is no particular fragility in a steel broken at blue heat (300-325° C.).

Guillet and Revillon carried out their tests on a Guillery 60 kgm. machine (see § 196 (3)). The test-pieces were heated in an electric furnace to slightly above the temperature required for the test, they were then placed on the anvil and the temperature noted at the time of fracture. The temperature was determined by the use of a thermo-couple inserted in a small hole drilled in the specimen and penetrating up to about 3 mm. from the cross section to be fractured.

The ends of the test-piece were covered with asbestos to prevent the cooling of the extremities when in contact with the anvil. Tests at as close to 100° C. as possible were obtained by heating in boiling water.

Aitchison has shown that with alloy steels the notched bar tests at high temperatures are a reflection of the tensile strength

of the steels, being more or less inversely proportional to that property. In all cases the steels gave higher value at elevated temperatures than they did under normal conditions.

Some tests on carbon steels at low temperatures, carried out at the National Physical Laboratory, are given in Table LXXV.

TABLE LXXV.

NOTCHED BAR TESTS AT LOW TEMPERATURES.

Tensile Test of Material at 17½° C.				Charpy Notched Bar Impact Test, on 5 × 5 × 27 mm. Specimens with 45° V Notch, 1 mm. Deep and 0·125 mm. Root Radius.		
Yield Stress. Tons per Sq. In.	Ultimate Stress. Tons per Sq. In.	Extension. Per Cent.	Reduction of Area. Per Cent.	Energy Absorbed in Fracture in Kg.M.		
				17½° C.	- 40° C.	- 80° C.
14	26·1	42·0	61	2·10	0·13	0·10
31	53·1	22·5	44	0·26	0·16	0·19
				Results are the average of five tests.		

Tests at the same temperatures on various alloy steels show that, generally, there is an appreciable drop in the energy absorbed in fracture between 17½° C. and - 40° C. but that between - 40 and - 80° C. the drop, if any, is small and in many cases there is a distinct rise in the value.

§ 219. **Ball Hardness Tests at Varying Temperatures.**—Felix Robin has shown that the curves connecting hardness and temperature are of the same general form as the tensile strength —temperature curves.

Aitchison[22] gives results of hardness tests at high temperatures on tungsten steels of various compositions ranging from 10 to 18 per cent. tungsten and from 0·2 to 0·7 per cent. carbon. Both investigators find a similar regular drop in the hardness as the temperature increases.

In § 186 it is pointed out that a dynamic hardness test is extremely useful for tests at high temperatures. Aitchison notes that his hardness tests were carried out by C. A. Edwards, so that it is probable that the results were obtained by the dynamic method described by Edwards in his paper read before the Institution of Mechanical Engineers.[32]

Hadfield [33] finds that the hardness of steel at the temperature of liquid air (– 185° C.) is double that given at normal temperature.

§ 220. **Alternating Stress Tests at Varying Temperatures.**—Very little experimental work has been carried out on the effect of high temperatures on the strength of materials under alternating stresses. Unwin [34] conducted some tests at a temperature of 200° C. and found that " the hot bars stood variations of stress rather better than the cold ones ".

Some tests carried out by the author on steel, having a primitive elastic of 21 tons per square inch, ultimate stress of 46 tons per square inch, per cent. extension of 26 and per cent. reduction of area at fracture of 52, gave the results given in Table LXXVI.

TABLE LXXVI.

ALTERNATING STRESS TESTS ON STEEL AT 20° C. AND 250° C.

Range of Stress. Tons per Sq. In.	Alternations Before Fracture.	Temperature. °C.	Remarks.	Limiting Range of Alternating Stress. Tons per Sq. In.
+ 18·2 to – 18·2	2,429,400	20	unbroken	+ 21 to – 21
+ 19·2 „ – 19·2	3,299,500	„	„	
+ 20·9 „ – 20·9	3,268,400	„	„	
+ 21·7 „ – 21·7	1,121,000	„	broken	
+ 23·7 „ – 23·7	3,240,000	„	„	
+ 24·6 „ – 24·6	1,996,900	„	„	
+ 16·5 to – 16·5	2,069,000	250	unbroken	+ 16·6 to – 16·6
+ 17·0 „ – 17·0	2,115,600	„	broken	
+ 17·2 „ – 17·2	313,050	„	„	
+ 18·8 „ – 18·8	383,750	„	„	

The tests were made in a machine of the Wöhler type, the test-piece running in an oil bath heated electrically, and show a reduction of 20 per cent. in the limiting range of stress by raising the temperature from 20° to 250° C. They were carried out at a speed of 2000 alternations per minute.

Tests on some rolled aluminium light alloys, by the same method, gave the results in Table LXXVII.

These results show that, whereas the average reduction in static strength by alteration of temperature from 20° to 150° C. is about 17 per cent., the corresponding reduction in the fatigue range is about 30 per cent.

TABLE LXXVII.

ALTERNATING STRESS TESTS ON ROLLED ALUMINIUM ALLOYS AT 20° C. AND 150° C.

No.	Ultimate Stress in Static Test. Tons per Sq. In.			Estimated Limiting Range of Stress in Fatigue. Tons per Sq. In.	
	20° C.	150° C.	200° C.	20° C.	150° C.
A	21·9	—	—	+ 6·5 to − 6·5	+ 5·5 to − 5·5
B	26·6	21·1	19·5	+ 10·5 „ − 10·5	+ 7·9 „ − 7·9
C	28·0	21·5	19·8	+ 10·2 „ − 10·2	+ 5·0 „ − 5·0
D	24·3	21·4	19·5	+ 10·2 „ − 10·2	+ 8·4 „ − 8·4
E	22·7	20·3	15·4	+ 9·0 „ − 9·0	+ 6·5 „ − 6·5

The average limiting elastic range (at 20° C.) for the five alloys (A to E) is about 75 per cent. of the static ultimate stress. With steel this value is of the order of 90 per cent.

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CHAPTER XXI.

TESTING OF TIMBER.

§ 221. EXAMINATION of the cross section of a sawn log of structural timber shows a central pith surrounded by concentric rings which are in turn encircled by the outer bark. Each ring represents the growth of one year in the life of the tree. These annual rings can be roughly divided into two sections, heartwood and sapwood, of which the inner or central portion (heartwood) is usually the stronger in mature trees.

Each annual ring itself consists of two parts, viz. the inner or spring wood and the outer or summer wood, of which the latter is the denser, harder and stronger. The strength of a piece of timber can therefore be roughly gauged by the proportion of summer wood in the annual rings.

The width of the annual rings indicates the rate of growth of the tree—rapid growth being shown by wide rings—they therefore give useful information as to the uniformity of growth. The rings are usually widest at the centre and become closer near to the bark. Their width and distribution often varies in different trees of the same kind, in various parts of the same tree and in different parts of the same cross section.

Timber is usually divided into two classes—hardwood and softwood. The former is derived principally from broad-leaved deciduous trees while the latter is obtained from evergreen conifers (needle-leaved trees). Exceptions to this classification are yew and long leaf-pine which are hardwoods although coming from conifers while horse-chestnut, poplar and basswood (broad-leaved trees) are softwoods.

Timber is used by engineers principally for structural purposes and a knowledge of its behaviour under various conditions of stress is necessary if it is to be used to the best advantage.

§ 222. **Density and Specific Gravity.**—The density of timber is largely affected by the percentage of moisture that it con-

tains, by its rate of growth, position in the tree and percentage of summer wood.

As the density is closely related to the mechanical properties of timber, its determination is of importance. It is usually ascertained by measuring and weighing carefully prepared pieces which, for preference, are made in the form of cubes or prisms. If b, t, and h are the three dimensions of the block in centimetres and W is the weight in grammes,

$$\text{then the specific gravity} = \frac{W}{b \times t \times h}$$

$$\text{and weight per cubic foot} = \left(\frac{W}{b \times t \times h}\right) \times g$$

where g is the weight of a cubic foot of water in lbs. (62·4).

For comparative results the moisture content must be the same, the density is, therefore, usually carried out on dried samples. For this purpose they are dried in an oven at 100° C. until of constant weight and the density calculated from this weight in conjunction with the dimensions (dry).

§ 223. **Percentage of Moisture.**—All the mechanical properties of timber are affected by the moisture content. The strength becomes less as the percentage of moisture increases. A determination of the percentage of moisture is always made from each test-piece and results which do not include this information are valueless.

The determination of the moisture content is made on pieces cut from each sample; in the case of tension, shear and cleavage tests these consist of pieces split off adjacent to the failure. From other pieces a disc or cube is taken from as near to the point of fracture as possible.

Discs, etc., are weighed immediately that they are cut, they are then dried in an oven with free circulation, and kept at a constant temperature of 100° C. until they cease to lose weight by further drying. They are then reweighed. The moisture contained is expressed as a percentage of the dry weight of the timber.

If w_w = weight before drying
w_d = weight after drying

$$\text{percentage of moisture} = \left(\frac{w_w - w_d}{w_d}\right) \times 100.$$

In order to hasten the drying process, the test-piece is sometimes cut into small match sticks or shavings bored from the

sample used. If this is done twelve hours drying is usually sufficient. Drying at 100° C. will eliminate all except about 2 per cent. of the moisture and this cannot be removed without igniting the sample.

Sections of beams are usually cut into small pieces for a moisture determination of each piece, in order to examine the distribution of moisture throughout the section. The results from such a determination on pieces of spruce and fir are given in Figs. 224 and 225.

§ 224. **Rings per Inch, Percentage of Sapwood and Percentage of Summer Wood.**—These estimations are usually made on the piece cut for percentage of moisture determination.

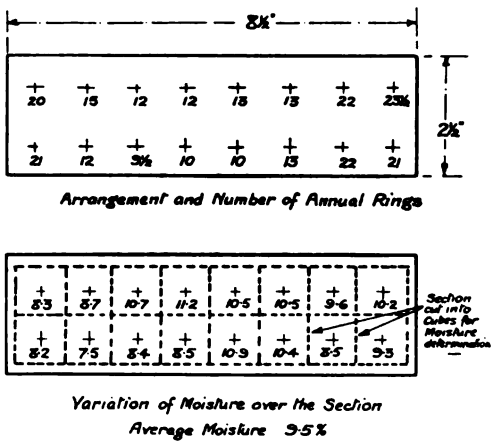
8½"
20 15 12 12 15 15 22 25½
21 12 9½ 10 10 13 22 21
2½"
Arrangement and Number of Annual Rings
8·3 8·7 10·7 11·2 10·5 10·5 9·6 10·2
8·2 7·5 8·4 8·5 10·9 10·4 8·5 9·3
Section cut into cubes for Moisture determination
Variation of Moisture over the Section
Average Moisture 9·5%

FIG. 224.—Distribution of moisture and number of annual rings per inch in a section cut from a plank of Christiania spruce.

A line, 1 inch long, is drawn on the cross section of the disc in a radial direction and passing through a region of average development.

The width of summer wood crossed by this line is obtained by spacing off accumulatively, on a pair of dividers, the width of the summer wood bands for each annual ring in succession. The final distance between the points of the dividers, in hundredths of an inch, is equal to the percentage of summer wood.

The number of rings per inch is obtained by noting the number of annual rings crossed by the measured inch.

The percentage of sapwood is estimated by measuring the

amount of the cross-sectional area in which sapwood appears and expressing this as a percentage of the whole area.

§ 225. **Drying Timber Test-pieces.**—In order to obtain reliable data from the various tests on timber, the information is usually referred to some standard percentage of moisture. It is considered that timber, if thoroughly dried, will reabsorb 12 to 15 per cent. of moisture from the atmosphere. Some experimenters therefore use 12 per cent. but the majority adopt 15 per

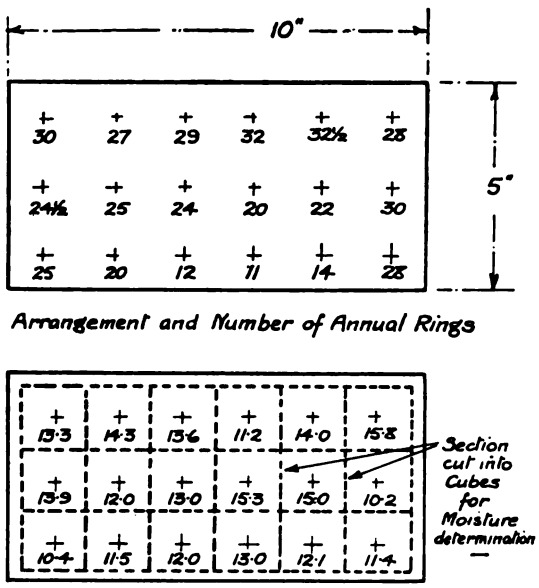
10"
5"
30 27 29 32 32½ 28
24½ 25 24 20 22 30
25 20 12 11 14 28
Arrangement and Number of Annual Rings
13·3 14·3 13·6 11·2 14·0 15·8
13·9 12·0 13·0 15·3 15·0 10·2
10·4 11·5 12·0 13·0 12·1 11·4
Section cut into Cubes for Moisture determination
Variation of Moisture over the Section
Average Moisture 12·9 %

FIG. 225.—Distribution of moisture and number of annual rings per inch in a section cut from a plank of Petersburg fir.

cent. as the standard for comparison. Tests are usually carried out at percentages of moisture above, below, and approximately at the standard, and for this purpose it is necessary to dry samples from the higher to the lower figure.

Two methods of drying are adopted, viz. air drying (or seasoning) and kiln drying, but owing to the long time required for successful air drying, kiln drying is usually resorted to for test work.

An experimental hot air drying oven or kiln, which has been

successfully used, is shown in Fig. 226. The samples are placed on a tray (A) in a circular vessel (B), which is heated by a gas burner (C), and a current of air is driven through this vessel by a rotary fan (D). A complete record of the temperature, which is never allowed to exceed 80° C., is obtained by a recorder which is placed alongside the test samples.

The test-pieces are prepared from the samples after drying and for this purpose the latter are usually left at least ½ inch larger on each of the cross-sectional dimensions and also considerably longer. Before drying in the kiln, the percentage moisture is obtained from pieces cut from each end of the sample, and from this information the reduction in weight which is

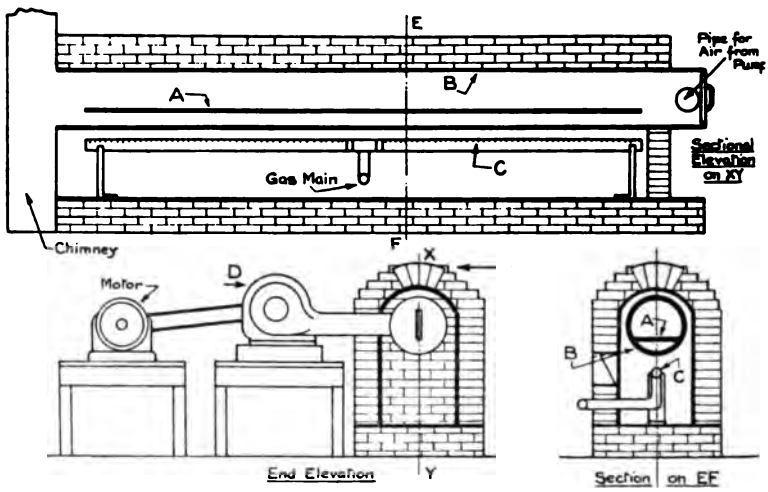

FIG. 226.—Experimental hot air oven or kiln.

required by the kiln drying in order to reduce the sample to the lower moisture content, is calculated. The drying of the test sample is continued until the reduction in weight is obtained.

§ 226. **Size of Test-pieces for Tests on Timber.**—Timber tests are divided into two classes:—

(1) "Scientific" tests of SMALL SPECIMENS free from knots or other blemishes and of uniform moisture content.

(2) Tests on FULL SIZE MEMBERS of structures—struts, beams, etc., which are not homogeneous and may contain serious defects.

Tests are necessary under both conditions. Large sections have the same strength per unit area as small ones when both are of the same proportions and similarly free from defects, but

under practical conditions it is found that this law of similarity is not realised and that tests on small pieces give values for the strength of timber in excess of the strength of large pieces.

§ 227. **Tensile Tests of Timber.**—All comprehensive investigations in regard to the strength of timber include a determination of its tensile strength as it is of scientific importance. The resistance of timber to tensile forces parallel to the grain is greater than under any other kind of loading. In timber structures the tension members are joined at their ends to other parts of the structure and the weakest point is the joint which is subjected to shear.

It follows that the tensile strength does not govern the strength of the member and, therefore, from a practical point of view it is of secondary importance.

The heads and shoulders of tensile test-pieces have to be very greatly enlarged, otherwise failure takes place either by shearing of the ends along the grain or by crushing of the ends

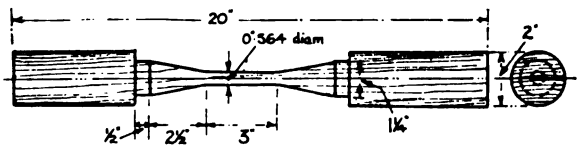

FIG. 227.—Tensile test-piece for timber.

across the grain. The type of test-piece adopted is shown in Fig. 227. The section to fracture is naturally small in comparison to the ends. Test-pieces similar to that shown in the figure but having the reduced diameter 1·25 inch instead of 0·564 inch are sometimes used.

§ 228. **Compression Tests on Timber.**—Compression tests along the grain give reliable indications of the quality of samples of timber. Failure usually takes place by shearing along planes inclined about 60° to 75° with the axis but sometimes by longitudinal splitting. The test-pieces (Fig. 228) are generally prisms 2 × 2 × 4 inches or 3 × 3 × 6 inches.

For investigatory work it is usual to determine stress-strain diagrams with the aid of a compressometer (§ 116). These give an initial portion of the curve which is approximately straight and it is customary from this curve to obtain the modulus of elasticity, and compressive stress at the limit of proportionality. Typical results are given in Table LXXVIII.

TABLE LXXVIII.

COMPRESSION (CRUSHING) TESTS ON TIMBER ALONG THE GRAIN.

Test-pieces 2 × 2 × 4 inches.

Timber.	Rings per In.	Moisture per Cent.	Limit of Proportionality. Lbs./Sq. In.	Crushing Stress. Lbs./Sq. In.	Modulus of Elasticity. Lbs./Sq. In.	Specific Gravity.
English Oak . .	7	24	2770	5300	$0{\cdot}99 \times 10^6$	0·76
" " . .	9	11	2530	5410	$0{\cdot}92 \times 10^6$	0·83
Fir (Russian) . .	18	14	6020	8940	$2{\cdot}60 \times 10^6$	0·74
Spruce (Christiania)	16	12	3200	4600	$1{\cdot}08 \times 10^6$	0·36
Fir (Columbian) .	24	12	7200	9990	$3{\cdot}10 \times 10^6$	0·78

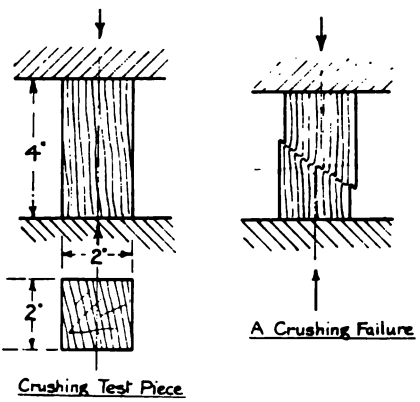

FIG. 228.—Crushing test on timber.

§ 229. **Shearing Strength of Timber.**—It is generally acknowledged by all authorities that accurate tests of the shearing strength of timber are difficult to make. Two methods have been adopted:—

(1) With the test-piece in double shear as indicated in Fig. 229.

(2) With the timber under single shear (Fig. 230). This method has been used with success by Warren.[1]

The resistance of various woods to shear across the grain has been determined by Trautwine [2] whose test-pieces were cylindrical pins $\frac{5}{8}$ inch diameter subjected to double shear.

§ 230. **Bending Tests.**—Bending tests are probably the commonest for timber, because of the great use of wood for rafters, joists, beams and other parts of structures subjected to

bending. Long pieces of fairly large section can be tested without testing machines of big proportions.

Test-pieces are usually rectangular, are supported at the ends

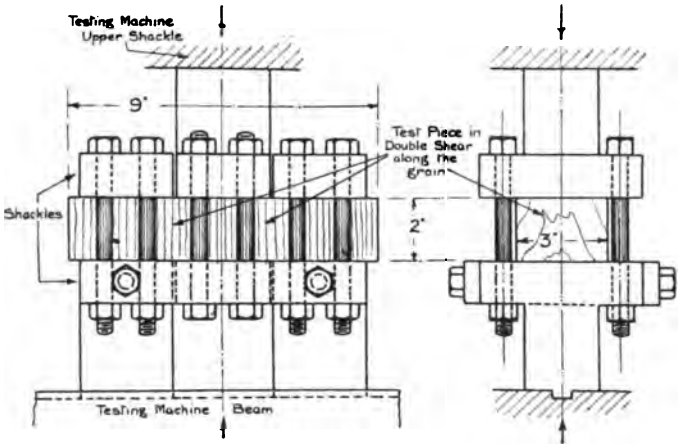

FIG. 229.—Timber tests (double shear).

and loaded either in the centre or at two points as indicated in § 49. The latter method (called four point loading) is now generally preferred as the maximum bending moment is spread

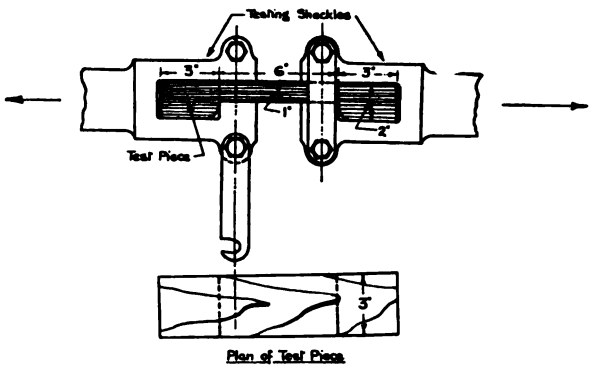

FIG. 230.—Tests on timber (single shear along the grain).

over half of the span and is not limited to the point directly under the application of the load as it is in the central loading method.

A sketch showing the direction of the grain at the ends and the number and arrangement of the annual rings should accom-

pany each test as well as an indication of the position and mode of fracture. The position and character of any defects such as knots should also be specially noted. Failure may take place by tension, compression or longitudinal shear along the grain.

For the determination of the limit of proportionality and coefficient of elasticity it is necessary to measure the deflection for known increments of the load. Instruments for doing this are described in §§ 119 and 120.

The strength factor usually measured is the modulus of rupture or coefficient of bending strength. Although a fictitious value, it is, nevertheless, a valuable index of the quality of the timber.

The various values obtained from the test data are calculated in the following way :—

If P = total load at the limit of proportionality
B = total load at fracture
l = span between the supports
b = width of cross section of the test-piece
h = depth of the cross section of the test-piece
d = measured deflection at the limit of proportionality.

For central loading (deflection measured on length = l).—

Greatest shearing stress $= \frac{3B}{4bh}$

Stress at the proportional limit $= \frac{3Pl}{2bh^2}$

Modulus of rupture $= \frac{3Bl}{2bh^2}$

Modulus of elasticity $= \frac{Pl^3}{4bh^3d}$

For four point loading (where the distance between the loading points = L, the space between the supports = l, and the deflection is measured on length l_1 in the section under uniform bending moment and l_1 is less than L. B and P are the sum of the two loads at the loading points).—

Greatest shearing stress $= \frac{3B}{4bh}$

Stress at the proportional limit $= \frac{3P(l - L)}{2bh^2}$

Modulus of rupture $= \frac{3B(l - L)}{2bh^2}$

Modulus of elasticity $= \frac{3P(l - L)l_1^2}{8bh^3d}$

Fig. 231 shows typical load deflection diagrams for Christiania spruce and Petersburg fir, while Figs. 232 and 233 give the load-

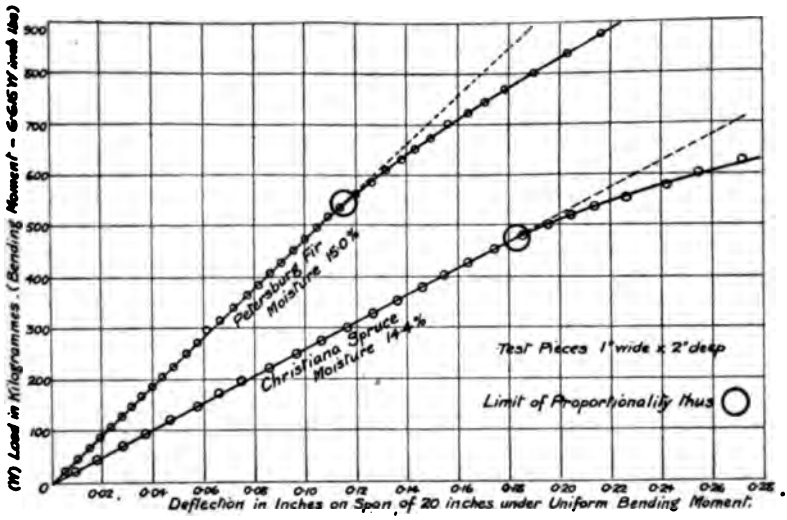
Petersburg Fir
Moisture 15.0%
Christiana Spruce
Moisture 14.4%
Test Pieces 1" wide x 2" deep
Limit of Proportionality thus
Deflection in Inches on Span of 20 inches under Uniform Bending Moment.

FIG. 231.—Load-deflection diagrams for Christiania spruce and Petersburg fir (bending test, four point loading).

extension diagrams in tension and compression for the same materials.

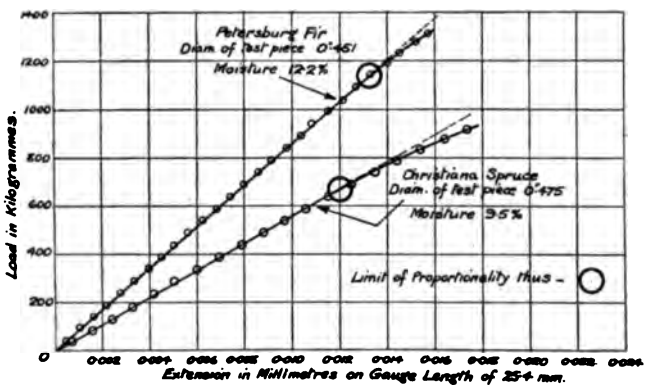

FIG. 232.—Load-deformation curves (tension) for fir and spruce.

§ 231. **Toughness Tests.**—Toughness is obtained by means of a notched bar impact test in which the energy absorbed by the

specimen is measured by the loss of energy in a swinging tup which breaks the material by a single blow. Fig. 234 shows the manner in which an Izod testing machine (see § 196 (i)) is

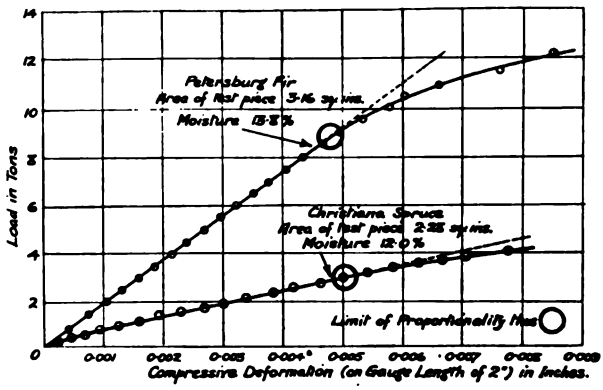
Load in Tons
Petersburg Fir
Area of fiat piece 3·16 sq ins.
Moisture 13·8%
Christiania Spruce
Area of fiat piece 2·25 sq ins.
Moisture 12·0%
Limit of Proportionality Pine
Compressive Deformation (on Gauge Length of 2") in Inches.

FIG. 233.—Load-deformation curves (compression) for fir and spruce.

utilised to carry out this test, and the form of test-piece is given in Fig. 235. The test-piece is notched with the annual rings as indicated in the sketch and the top of it, where the tup strikes, is protected by a steel plate.

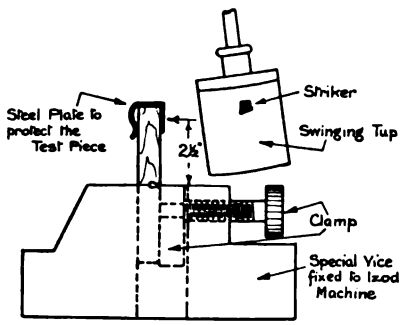

FIG. 234.—Tests on timber (notched bar impact test for toughness).

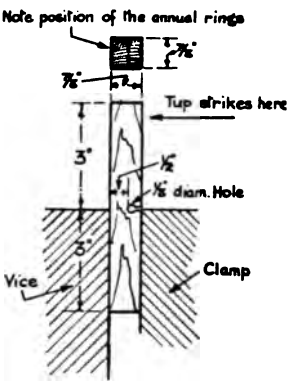

FIG. 235.—Notched bar test-piece for timber.

§ 232. **Impact Bending Test.**—In this test the specimen (2 × 2 × 30 inches) is supported at the ends on a span of 28 inches. The load is applied by dropping a hammer upon the specimen at mid span, from an initial height of 1 inch. For suc-

ceeding drops the height is increased by 1 inch increments up to 10 inches, and thereafter drops are made at successive increments of 2 inches, until failure. Hammers of 50, 100 and 250 lbs. are used.

Deflections of the specimen are measured with each drop and a curve is drawn connecting height of drop and deflection squared. Deflections are obtained from a drop curve traced on a revolving drum.

If W = weight of the hammer
H = height of drop at elastic limit
F = fibre stress at elastic limit
D = central deflection of specimen at elastic limit
b = breadth of specimen
h = height of specimen
L = span

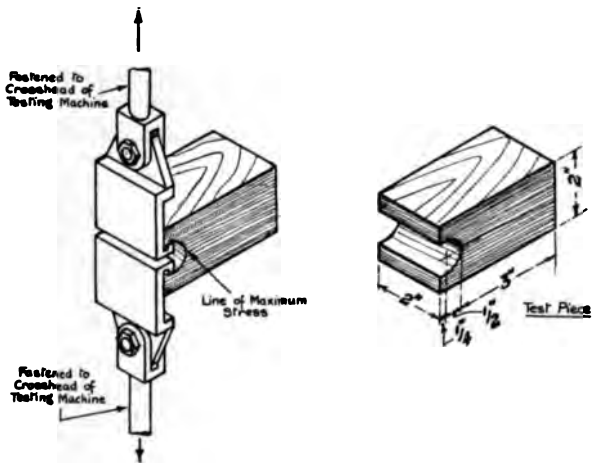

FIG. 236.—Cleavability test.

Then—

$$\text{Fibre stress at elastic limit} = \frac{3WHL}{Dbh^2}$$

$$\text{Modulus of elasticity} = \frac{L^2 \times F}{6Dh}$$

$$\text{Work to elastic limit} = \frac{WH}{bhL}$$

§ 233. **Cleavability.**—For the resistance to splitting, the U.S.A. Department of Agriculture use the test-piece indicated in **Fig.** 236 and express the results in lbs. per inch of width at

fracture. Tests have been carried out to determine the resistance to splitting radially as well as tangentially to the annual rings, and the results (Table LXXIX) show that most hardwoods split more easily along radial planes than along tangential surfaces.

TABLE LXXIX.

Kind of Timber.	Cleavage Strength in Pounds per Inch of Width.	
	Radial.	Tangential.
Hardwoods—		
Ash . .	322	316
Elm . .	297	357
Oak . .	370	462
Softwoods—		
Fir . .	138	149
Hemlock .	168	151
Yellow pine	155	173
Spruce .	120	139

Splitting is related to tensile strength across the grain. A high value is advantageous for timber which has to be fastened by nails or spikes.

§ 234. **Hardness Tests on Timber.**—The ball hardness test has been applied to timber in two ways :—

(1) The first method, adopted by Warren,[1] follows the Brinell test for metals, viz. a ball of fixed diameter is pressed into the timber under a known load maintained for a stated time. The hardness number is calculated from the formula—

$$H = \frac{P}{A}$$ where H = the hardness number

P = the load in kilograms

A = the projected area of the indentation $\left(\frac{\pi d^2}{4}\right)$.

Warren uses a ball of 20 mm., load of 1000 kilos and time of 2 minutes. He found that the hardness along the fibre is considerably greater than either parallel or perpendicular to the annual rings.

(2) The second method, largely used in the U.S.A., is to press a ball of 0·444 inch diameter into the timber until it has penetrated 0·222 inch. The load required is taken as a measure

of the hardness. The test tool is a steel bar with a hemispherical end. This end projects through a hole in the bottom of a cup-shaped washer. When the tool has penetrated the timber to the correct depth there is binding between the steel bar, washer, and specimen. The load at that instant is noted.

With the Ludwik cone test Warren[1] uses the standard 90° cone and a pressure of 400 kilograms applied for 1 minute. The depth is measured by an indicator as the test proceeded.

§ 235. **Resistance of Timbers to Abrasion and Wear.**— Relative wear has been tested by pressing blocks of the material 2 × 2 inches under a pressure of 26 lbs. against a table covered with fine sand-paper and revolving at 68 revolutions per minute. A better method was used by Warren,[1] who utilised a sand blast. The test-piece 3 × 3 × 1 inches was clamped against a plate having a 2½-inch hole in it and together with the plate was rotated about its own axis. A jet of superheated steam under a pressure of 43 lbs. per square inch, carrying sand in it, was projected through an expanding nozzle on to the surface of the rotating test-piece. The sand blast wore away the wood on the exposed diameter of 2½ inches and the loss of weight of the test-piece in 2 minutes exposure gave a measure of the wearing quality of the wood. Tests were made—

(*a*) Parallel to the direction of the fibre.

(*b*) Perpendicular to the direction of the fibre and perpendicular to the annual rings.

(*c*) Perpendicular to the direction of the fibre and tangential to the annual rings.

The results showed that the wear was least parallel to the direction of fibre. The ratio in the three directions being $a : b : c = 1 : 2\frac{1}{2} : 4$.

§ 236. **Holding Power of Nails and Spikes in Wood.**— Nails hold in timber by virtue of the friction developed between the surface of the nail and the fibres of the timber. An investigation into the holding power of nails and spikes in Australian timber was carried out by Warren in 1911, who found that Australian timbers were so hard that it was necessary to first bore a hole slightly smaller than the nail in order to prevent either buckling of the nail or splitting of the timber. Six-inch No. 1 S.W.G. smooth steel wire nails were driven to a depth of 3½ inches in the timber in holes bored to $\frac{9}{32}$ inch diameter. They were withdrawn by pulling in the testing machine, and the loads to pull from various depths were noted.

The results showed that the holding power was approximately proportional to the depth, as shown in Table LXXX.

TABLE LXXX.

HOLDING POWER OF NAILS.

Depth Driven in Inches.	Mean Load in Lbs.
$1\frac{1}{2}$	1438
2	2201
$2\frac{1}{2}$	2676
3	3158
$3\frac{1}{2}$	3529

For driving spikes, holes slightly smaller than the diameter of the spike must be drilled. Warren found that $\frac{3}{4}$ inch square section twisted spikes required 30 per cent. more load to withdraw them than $\frac{3}{4}$ inch square or $\frac{7}{8}$ inch circular black iron straight spikes.

Hatt,[3] experimenting with $\frac{9}{16}$ inch to $\frac{5}{8}$ inch square, smooth spikes and screwed spikes, pitch $\frac{1}{2}$ inch, root diameter $\frac{11}{16}$ inch, driven in $\frac{11}{16}$ inch holes to a depth of 5 inches, found that the plain spikes had about 55 per cent. of the resistance of the screwed ones. Hatt's results agreed with those of Warren in showing that the holding power was proportional to the depth.

§ 237. **Influence of Conditions of Tests upon Results.**—(*a*) **The Effect of Moisture.**—The effect of moisture on the strength of wood has been thoroughly investigated by Tiemann,[4] and his results, which are fully given by Johnson,[5] show that there is a large increase in crushing strength, modulus of elasticity and modulus of rupture, with a decrease in the moisture content. Table LXXXI gives the approximate figures for spruce, chestnut, and pine.

TABLE LXXXI.

EFFECT ON TEST RESULTS OF VARYING MOISTURE CONTENT.

Material.	Per Cent. Increase in Value by Drying from 20 per Cent. to 10 per Cent. of Moisture.		
	Crushing Strength.	Modulus of Elasticity.	Modulus of Rupture.
Eastern spruce . .	62	14	52
Chestnut . . .	59	25	44
Long-leaf pine . .	89	21	47

(*b*) **Effect of Temperature of Testing.**—The ordinary variations of temperature of the laboratory (15° to 25° C.) are not important, but if greater extremes occur it is advisable that the temperature at which the tests are carried out should be controlled. Tests made at Perdue University show an increase in the strength of red oak ties of from 9 to 17 per cent. by testing them at 0° instead of 20° C.

(*c*) **Effect of Speed of Testing.**—Thurston[6] found that 60 per cent. of the breaking load given by progressive loading on the ordinary testing machine would break beams if left in place for nine months. Experimenting on the same subject, Johnson[7] determined that it was not safe to assume that the permanent load which timber would carry was greater than 50 per cent. of the short time ultimate load as ordinarily found by the testing machine.

It is evident, therefore, that the influence of time must be allowed for in testing wood. As a result of work by Tiemann,[8] the U.S.A. Forest Service of Agriculture have standardised fibre strain in testing, as given in Table LXXXII.

TABLE LXXXII.

Bending tests on timber of structural size . .	0·0007 in. per min. per inch
Bending tests on small beams	0·0015 ,, ,, ,,
Compression parallel to grain, large test-pieces .	0·0015 ,, ,, ,,
Compression parallel to grain, small test-pieces .	0·0030 ,, ,, ,,
Shearing along the grain	0·0150 ,, ,, ,,

The strength of wet or green wood is much more sensitive to changes of speed than is dry wood. A change of the above speeds by 50 per cent. may ordinarily be allowed without causing a variation in strength of over 2 per cent.

The modulus of elasticity in bending was found to be practically constant with change of speed.

REFERENCES FOR CHAPTER XXI.

[1] Warren, Report of the Department of Forestry, N.S.W., Australia, 1911, on "N.S.W. Hardwood Timbers".
[2] Trautwine, "Franklin Inst. Jour.," Vol. CIX, p. 106.
[3] Hatt, Bull. No. 124, Am. Ry. Engr. Assn.
[4] Tiemann, Bull. 70, U.S.A. Forest Service, 1906, and Circular No. 108, 1907.
[5] Johnson's "Materials of Construction," 1918 edition, p. 195.
[6] Thurston, "Materials of Construction," Part II.
[7] Johnson's "Materials of Construction," 1918 edition, p. 208.
[8] Tiemann, "Amer. Soc. Test. Mat. Proc.," 1918, Vol. VIII, p. 541.

CHAPTER XXII.

TESTING OF STONE, BRICK AND CONCRETE.

§ 238. THE important characteristics of stones and bricks from an engineer's standpoint are ease of working, durability and strength. Durability depends on resistance to—

(*a*) Abrasion or attrition.
(*b*) Absorption of water.
(*c*) Alternate freezing and thawing.
(*d*) Fire.
(*e*) Acid.

Stones and bricks are subjected in practice to compression, sometimes to transverse stress and shearing, but not to tension, except such as would be caused by wind pressure or other lateral forces. Besides resistance to these forces the specific gravity is an important property. For a given stone the specific gravity and strength increase concurrently, while for some purposes greater stability is given by higher specific gravity.

With concrete a knowledge of its elastic constants and tensile strength, of its resistance to fatigue and permeability to water are requisite for the purposes of design.

If the percentage of cement is constant the strongest concrete is usually the one which has the greatest specific gravity, i.e. the least proportion of voids.

§ 239. **Determination of Specific Gravity.**—In order to determine the specific gravity (including the pores) the sample is dried at 100° C. until it is of constant weight and when cool coated with a thin film of paraffin wax and weighed in air and water.

If W_a = weight in air and
W_w = weight in water.

$$\text{The specific gravity} = \frac{W_a}{W_a - W_w}.$$

A correction for the film of paraffin wax can be made if the results are required to a high degree of accuracy.

The true specific gravity of the stone substance is obtained by grinding the dry stone to a powder and determining the specific gravity of the powder with a standardised Le Chatelier apparatus or similar form of specific gravity apparatus.

The porosity of the material can be obtained by making both the above determinations.

Then, if S_s = specific gravity of the stone substance and the other values are as before :—

$$\frac{W_a - W_{w'}}{\text{wt. of a cub. unit of water}} = \text{vol. of the stone + pores} = A$$

$$\frac{W_a}{\text{wt. of a cub. unit of water} \times S_s} = \text{vol. of the stone substance} = B.$$

Then the porosity $= \frac{A - B}{A}$.

§ 240. **Absorption of Water.**—The usual method of obtaining the amount of water which stone, brick or concrete will absorb is to immerse the specimen in water at approximately 20° C. after it has been dried at 100° C., cooled and weighed. The immersion is continued for three days when the surface water is removed and the material is reweighed. The increase in weight divided by the original weight and multiplied by 100 gives the percentage absorption. The process is sometimes hastened by eliminating the long period of soaking, and immersing the test-piece in water which is slowly raised to boiling point and kept at that temperature for five hours.

A slight modification is sometimes introduced by weighing the specimen in air (W_a), in water immediately after immersion (W_w), and also in water after three days immersion (W^1_w).

Then the absorption in pounds of water per cubic feet of material—

$$= \frac{W^1_{w'} - W_w}{W_a - W^1_w} \times 62{\cdot}37.$$

§ 241. **Alternate Freezing and Thawing.**—This test is made by subjecting the specimen to a temperature of − 10° to − 20° C. for at least four hours after it has been thoroughly saturated with water. It is usual to apply ten alternate freezings and thawings and then employ the crucial test of crushing.

§ 242. **Abrasion and Attrition.**—Bauschinger [1] devised an abrasion test for stone which consisted in pressing a 4-inch cube of the material, under pressure of four lbs. per square inch, against an iron plate rotating at 20 revolutions per minute.

The test-pieces were fixed at a radius of 19½ inches and the abrasive employed was fine emery (No. 3) fed on to the plate at the rate of 2 grammes per revolution.

This test does not differ greatly from the Dorry test for road stones (§ 260).

The sand blast test (see § 235) was used by Gary[2] as an additional abrasion test for stone. He gave comparative results by the two methods, together with the crushing strength, these are given in table LXXXIII.

TABLE LXXXIII.

RESULTS OF ABRASION TESTS ON BUILDING STONES BY GARY.

Area of specimens used on grinding table = 7·75 sq. in.
Diameter of nozzle on sand-blasting device = 2·36 inches.

Kind of Stone.	Compressive Strength in Lbs. per Sq. In.	Vol. of Wear in Cubic Inches per Sq. In.		
		On Grinding Table.	With Sand Blast.	
			Perpendicular to Rift.	Parallel to Rift.
Basalt . . .	38,900	0·042	0·024	0·025
Granite . . .	21,360	0·041	0·037	0·052
Gneiss . . .	21,230	0·079	0·056	0·045
Porphyry . . .	17,840	0·068	0·046	0·036
Graywacke* . .	15,780	0·085	0·059	0·058
Sandstone . .	6,640	0·144	0·155	0·117
Slate . . .	7,480	0·234	0·111	0·082

* A dense sandstone containing rounded or angular particles of quartz, felspar or slate.

A "rattler" test is used in the U.S.A. for paving brick, and the conditions of the test have been standardised.[3] It consists in placing ten samples of the material in a cylinder together with an abrasive charge consisting of twenty cast-iron spheres of two sizes. The loss in weight is calculated as a percentage of the initial weight of the samples. This test is somewhat similar to the Deval attrition test or Lovegrove rattler test for road stones (see § 258).

§ 243. **Testing the Wearing Quality of Concrete Flags.**—A special form of rattler test is specified by the Institution o Municipal and County Engineers for testing the rate of wear of concrete flags.

Samples of the flags t_1, t_2, t_3 and t_4 (Fig. 237), 2 feet by 1 foot,

form the sides of a rectangular container (R) which is designed so that there is a definite area (22 × 10 inches) of the wearing face of each flag exposed on the inside of the vessel. The ends (E and F) of the container are solid and are keyed to

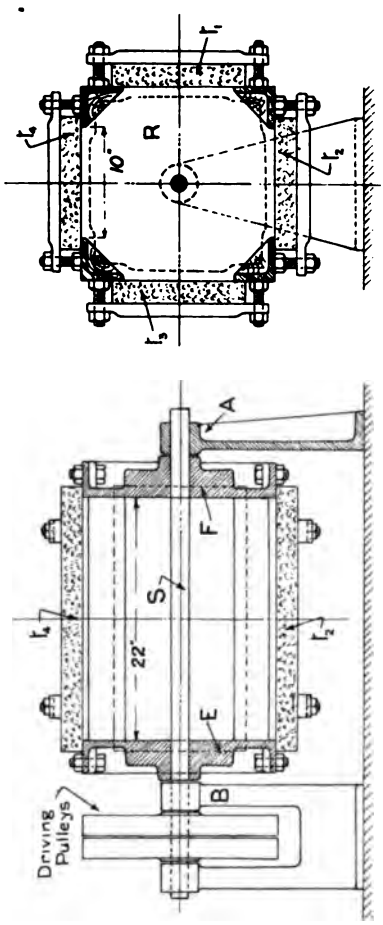

FIG. 237.—Wear testing machine for concrete flags.

a shaft (S) which goes through the vessel and is supported on bearings A and B.

1000 hard steel or chilled iron balls, $\frac{1}{2}$ inch but not less than $\frac{7}{16}$ inch in diameter, are placed in the container to act as an abrasive and the apparatus is revolved for 24 hours at a uniform

speed of 60 revolutions per minute in one direction and for a further 24 hours at the same speed in the reverse direction.

Before the test the specimens are dried to a constant weight at a temperature not exceeding 100° F. and after the test they are brushed clean of dust and the loss of weight obtained. This should not exceed 1·5 lb. on each specimen which should also show uniform wear over the surface.

Steel plates can be fixed in position instead of flags if there are insufficient test-pieces to cover the four openings in the container.

§ 244. **Crushing Test.**—The crushing strength is usually accepted as being the criterion of the mechanical qualities of brittle materials, such as stone, brick and concrete.

In carrying out this test the kind of bedding employed has a great influence on the results. Unwin [4] has shown that fluidity of the bedding produces vertical splitting of the test-piece and a considerable reduction of the crushing strength. The common practice of putting wood or lead layers in between the test-piece and the testing machine compression blocks, in order to allow for irregularities in the surface of the specimen and to distribute the pressure over that surface, is erroneous. In order to obtain plane parallel faces, Unwin's method of applying thin layers of plaster of paris has been used by the authors for a considerable number of tests without obtaining any unsatisfactory fractures.

A series of tests were carried out by Foeppl,[5] who found that test cubes of cement, sandstone and granite broke down, in compression, with half and in some cases one-third or one-quarter their usual crushing load when the end surfaces were greased with stearine or wax.

The information obtained from the test is the stress at which the first crack appears and the ultimate crushing stress. It is essential that the load should be applied axially and the compression blocks are usually supplied with spherical seatings (see § 48). It is essential that the upper adjustable block should be kept in motion as the head is brought to a bearing on the specimen thus insuring a central bearing and preventing the test-piece from being pulled aside.

Crushing Test-pieces.—For geometrical similar test-pieces the crushing strength is proportional to the cross-sectional area, so that by the use of cubes a true *comparison of* the strength of various samples can be obtained. The strength is, however, dependent on the ratio of the height to the width of the test-piece

up to a value of about two. Above this ratio, experiments show that the effect is small. The theoretical angle of crushing is 60° with the horizontal.

Test-pieces should be made by an experienced workman and the material should be worked in the mould by tamping and gentle ramming.

In English practice crushing test-pieces of building stone are usually in the form of cubes of 4-inch sides, for concrete cubes of from 7 to 10-inch sides are employed, while bricks are generally tested on the flat. Bricks are sometimes broken in halves, one piece being tested for crushing strength dry while the other piece is tested for absorption of water and crushing strength wet. The dimensions of the test-pieces and, with bricks, direction of crushing are always given with the results.

In America, cylindrical test-pieces are recommended of the following sizes:—

8 inches diameter and 16 inches long for concrete.
6 inches diameter and 12 inches long for stone.
2 inches diameter and 4 inches long for mortar.

Cast iron is preferred to wood for moulds as the latter, even when saturated with oil or coated with paraffin, is liable to absorb water from the sample.

§ 245. **Effect of Water on Strength.**—The compressive strength of concrete is reduced, by an excess of water during mixing, to a fractional part of that which it would reach under proper conditions (see Table LXXXIV).

TABLE LXXXIV.

EFFECT OF PERCENTAGE OF WATER ON THE CRUSHING STRENGTH OF CONCRETE (FROM U.S. SURVEY BULL. No. 344).

Percentage of Water.	Concrete 1 : 2 : 4 by Volume, Strength in Lbs. per Sq. In.			
	Crushing.		Modulus of Rupture (Bending).	
	1 Month.	6 Months.	1 Month.	6 Months.
9·8	2299	3814	391	435
9·0	3547	4808	451	520
7·9	4612	4884	426	496

§ 246. **Results of Tests.**—Representative crushing, bending and absorption results on stone and brick are given in Table LXXXV.

TABLE LXXXV.

STRENGTH OF STONE AND BRICK.

	Crushing Strength. Lbs. per Sq. In.	Transverse Test, Modulus of Rupture. Lbs. per Sq. In.	Absorption. Per Cent.
Stone—			
Granite	13,000-25,000	2710-3910	0·4-1·0
Limestone	2000-9100	1160-4660	0·3-6·4
Sandstone	4900-11,000	360-1320	0·7-8·2
Bricks—			
Vitrified brick	5000 and over	over 900	less than 5
Hard burned	3500-4999	600-900	5-12
Common firsts	2000-3499	400-600	12-18
Common	1500-1999	300-400	over 18
Leicester wire cut	3600-5300	—	—
Fletton	2600-3900	—	—
White gault, wire cut	2100-3100	—	—
Aylesford red pressed	2200	—	—
London best stocks	1600-2800	—	—
Common stocks	1250-1900	—	—

Crushing results to be expected from a good concrete of the proportion of 1 cement, 2 sand and 4 stone are given in Table LXXXVI, while Table LXXXVII gives the minimum values required by the standard specification for reinforced work of the Concrete Institute.

TABLE LXXXVI.

RESULTS EXPECTED FROM A GOOD CONCRETE.

Cement 1
Sand 2 } by volume.
Stone 4

Age of Concrete.	7 Days.	14 Days.	28 Days.	1 Year.	2 Years.
Crushing strength in lbs. per sq. in.	1300	1600	2000	3500	4000

NOTE.—These figures assume that moisture has had access to the concrete.

Concrete made from broken hard stone bears compressive loads 8 to 10 per cent. stronger than similar concrete made with gravel, while dirty gravel may reduce the strength by as much as 25 per cent.

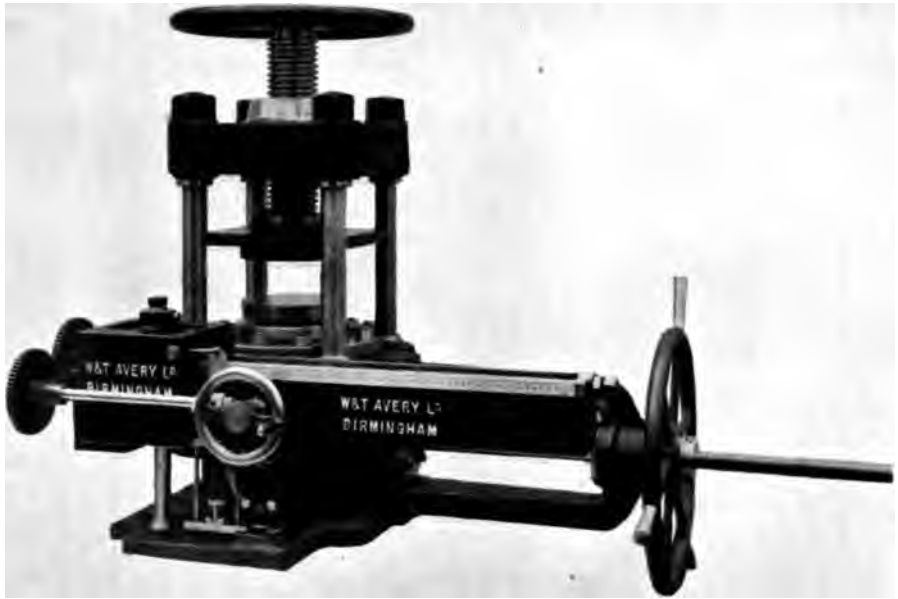

Fig. 238.—50-ton lever compression machine.

[*See p.* 365.

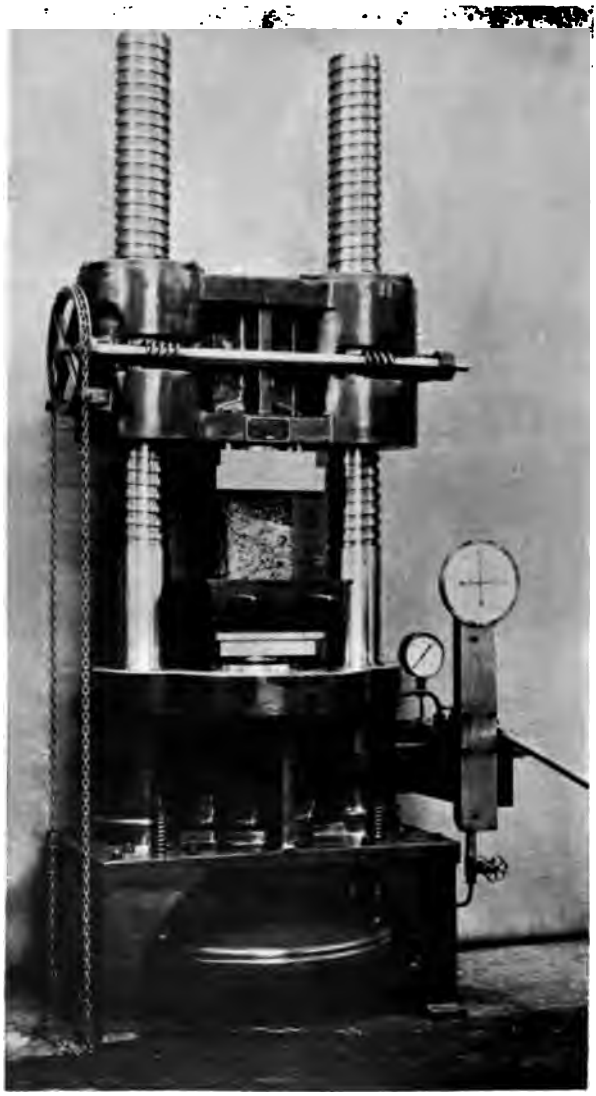

FIG. 239.—500-ton compression machine.

[*To face p.* 365.

TABLE LXXXVII.

MINIMUM CRUSHING STRENGTH OF CONCRETE FOR REINFORCED CONCRETE WORK.

Proportion by Volume.			Crushing Stress in Lbs. per Sq. In.	
Cement.	Sand.	Coarse Material.	At 28 Days.	At 120 Days.
1	2	4	1600	2400
1·2	2	4	1800	2600
1·5	2	4	2000	2800
2	2	4	2200	3000

§ 247. **Testing Machines for Compression Tests of Cement, Concrete, etc.**—Where a considerable number of tests have to be carried out in compression, it is usual to install a special machine for the purpose. When dealing with concrete, stone and cement it is generally adequate if the machine is capable of reading accurately to one-twentieth of a ton. For this reason, as well as to the fact that a relatively small deformation suffices, the apparatus can be made fairly simple in construction.

(i) **50-ton Compression Machine-lever Measurement of Load.**—Fig. 238 shows the Avery type of small compression machine taking a maximum size of test-piece of 6-inch cube with a testing capacity of 50 tons. The test-piece is placed between two platens, the upper one of which is adjustable and can be brought into contact with the lower one enabling thin specimens to be tested. The lower platen (which has a spherical seat) rests upon a hydraulic ram, which is forced upwards by means of a screw compressor; the pressure of the fluid in this cylinder is conveyed to a small subsidiary cylinder and ram, at the end of which latter a knife edge is fixed. This communicates the strain to the steelyard where it is balanced off by the movement of a poise traversing suitable graduations.

The steelyard is divided into tons and fifths of a ton while a Vernier on the poise enables loads of 0·02 ton to be read. The poise is propelled by the usual Avery method, employing a central screw and gear wheels.

(ii) **500-ton Compression Machine.**—A machine for compression tests (Fig. 239), installed at the National Physical Laboratory, embodies an interesting method of measuring the load. It is constructed by Alfred J. Amsler & Co., and is of

the ordinary hydraulic type, the pressure being applied by a two-piston oil pump arranged horizontally in an oil reservoir attached to the side of the press.

The oil pump can easily be operated by one man up to the full capacity of the machine (500 tons).

The machine takes specimens, from 0 to 105 centimetres long and up to 30 centimetres square in cross section, between compression plates working in spherical seatings. The machine weighs 9000 lbs., is 10 feet high and requires no special foundation.

Load Measurement.—The value of the load is derived from the elastic elongation of the two main columns of the machine. The lower parts of these columns (i.e. below the screw threads) are hollow and take the full load applied to the specimen without exceeding the limit of proportionality of the material of which they are made.

The elongation of the columns is proportional to the force transmitted, and is measured by means of the relative movement of a disc piston (P, see Fig. 240) attached to rods (R_1, R_2) suspended in the interior of the columns (A_1, A_2) and a cylinder (C) which bears against the lower ends of each column.

The disc piston (P) is connected to the cylinder (C) by means of a diaphragm (D), and the space between them is filled with water into which some non-corroding liquid has been added. The suspended rods (R_1, R_2) are connected to the disc piston by spherically seated nuts (N_1, N_2) and a clearance (T) is provided between the rods and the cylinder. A special gland (G_1, G_2) is inserted round the rods which, although it allows movement between the disc piston and cylinder, prevents any leakage of liquid from the space between them.

Upon application of the load the two main columns (A_1, A_2) stretch and the rods (R_1, R_2) raise the disc piston (P) in the cylinder (C), so that liquid from the space between them is driven through the opening (B) into a vertical tube seen in the bottom right-hand corner of Fig. 239.

The vertical tube contains an ebonite float which, as it moves upwards due to the rising liquid, rotates a pointer over a graduated dial by means of a pulley and thread. The dial is calibrated in terms of the load applied and 0·1 of a ton can easily be estimated up to the full capacity of the machine.

It is advisable when using this machine to constantly check the zero reading. The apparatus is very susceptible to changes of temperature and it is expedient to see that the zero is unaltered before each test. This temperature change of zero is a

disadvantage if the test takes any great length of time such as is necessary when making a compressometer test. A screw plunger

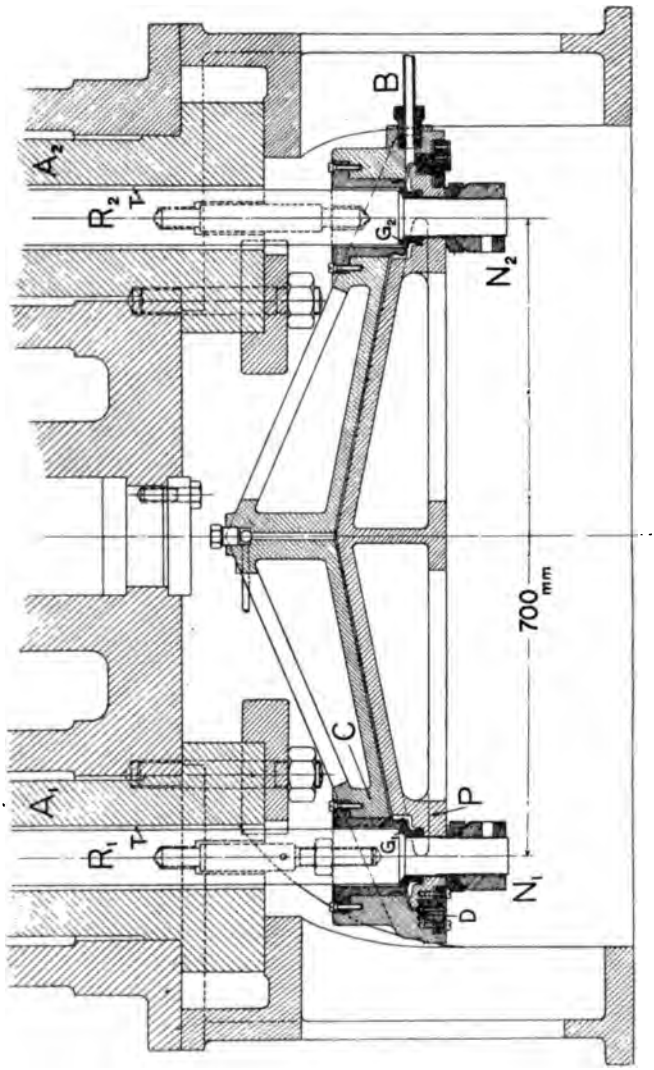

FIG. 240.—Disc piston arrangement for Amsler 500-ton compression machine.

is fitted to the vertical tube to enable the pointer of the load dial to be adjusted exactly to zero by displacing the liquid.

The working distance between the two platens is varied by

adjusting the movable cross-head by means of circular nuts operated by right and left-hand worms turned by a wheel and hand chain.

§ 248. **The Elastic Properties of Stone, Brick and Concrete.**—It has been shown that a linear relation is often not obtained between stress and strain for stone, brick and concrete (§ 136), and that for the latter empirical modulii are used for the purposes of design calculation.

Stanton Walker[6] gives the following particulars of the manner in which different variables affect the strength and modulus of elasticity of concrete:—

"(*a*) Both the modulus of elasticity and strength increase within certain limits as the aggregate becomes coarser, although the modulus of elasticity increases less rapidly than the strength.

"(*b*) An increase in the quantity of cement in the batch causes an increase in the values of the modulus of elasticity and the strength. The modulus of elasticity is affected somewhat less by change in the cement content than the strength.

"(*c*) The quantity of mixing water exerts a most marked effect on the modulus of elasticity and strength. An addition of 25 per cent. of water to a mixture of normal consistency decreases the modulus of elasticity about 15 to 20 per cent., and the strength about 35 to 40 per cent.

"(*d*) Both the modulus of elasticity and strength increase with the age of the concrete so long as the specimens are kept moist during curing. The strength increases in proportion to the logarithm of the age. The modulus of elasticity follows approximately the same relation.

"(*e*) There is no marked difference in the modulus of elasticity and strength of concrete made from high grade pebbles, crushed limestone, crushed granite or blast furnace slag.

"(*f*) A comparison of specimens stored fourteen days in damp sand and seventy-seven days in air with specimens stored ninety-one days in damp sand shows that the modulus of elasticity and strength are higher for the damp sand storage.

"(*g*) Tests for mixing times ranging from ¼ to 10 minutes show that both the modulus of elasticity and strength are greater for the longer mixing times."

A large number of careful compressometer tests have been made by Lea[7] who says that "the modulus of elasticity of concrete is a very variable quantity, but for a particular mixture the modulus can be fairly definitely obtained by determining the slopes of the third or fourth loading stress-strain curves, taken

from blocks of concrete three months old, and that the values so obtained will approximate very closely to those determined from strain tests on beams". He finds that the values of the modulus of elasticity in compression vary as the crushing stress and that one is indicative of the other, the stronger mixtures having the larger modulus. In general it is found that the values of the modulus in lbs. per square inch is roughly 1000 times the crushing stress in lbs. per square inch.

Lea finds further that compressometer tests on columns, as well as bending tests on beams, show that it is very difficult to ensure uniform distribution of stress in concrete. He suggests that an allowance, on account of this, of 10 to 20 per cent. of the mean stress calculated from the ordinary formulæ should be made when designing columns and beams.

§ 249. **Effect of Temperature on the Strength of Concrete.** —Lea [8] finds that the crushing strength of concrete appears to be little affected by heating up to a temperature of 450° C. Above this temperature the falling off in strength is very large and seems to be due to loss of bond between the materials. At 630° C. the crushing strength is reduced by 80 per cent.

When heated to 430° C. and tested hot he found concrete (composition 1-2-4) 10 per cent. to 12 per cent. stronger than when tested after being heated to the same temperature and allowed to cool.

§ 250. **Tensile Strength of Concrete.** — Considerable difficulty is experienced in designing suitable end attachments for tensile tests on concrete. Many experimenters cast spherically headed bolts in the centre of the ends of the test-piece and pull on these heads by the testing machine grips, others enlarge the ends so as to form the test-piece into a flat dumb-bell shape. Particulars of a few dimensions which have been adopted are given in Table LXXXVIII.

The tensile strength of concrete is about $\frac{1}{8}$ to $\frac{1}{10}$ of the crushing strength.

§ 251. **Shear Strength of Concrete.**—The shear strength of concrete usually lies between $\frac{1}{2}$ and $\frac{3}{4}$ of the crushing strength. The shear testing tool is of the same form as that used for metals (§ 50 (i)) but is specially arranged to take a larger test-piece. The test-pieces are generally cast 5 or 6 inches in diameter and 14 to 18 inches in length and are tested in either single or double shear.

TABLE LXXXVIII.

PARTICULARS OF TENSILE AND COMPRESSION TEST-PIECES FOR CONCRETE.

Authority.	Tensile Test-piece.	Crushing Test-piece.
[illegible]	2½ × 3½ × 21-in. prisms	2½ × 3½ × 11-in prisms
[illegible]	6 × 6 × 18-in. prisms	6-in. cubes
[illegible]	4 × 4 ins. : 1 sq. in. 17½ ins gauge length	8 ins. diam. × 12 ins. cylinders
[illegible]	square cross section, enlarged ends	6 × 6 × 14-in. prisms
St. Louis Testing Laboratory	3 × 3 ins. square section enlarged ends, 5 in. long	4½ ins. diam., 5½ ins. deep (cylinders)

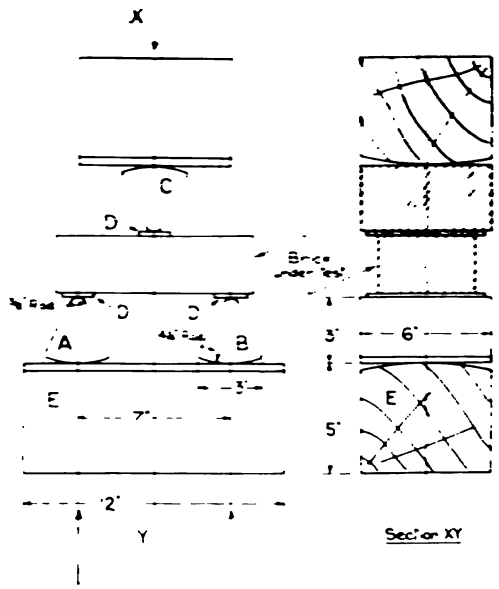

FIG. 241.—Transverse test on bricks.

§ 252. **Transverse Strength of Bricks.**—A method of carrying out transverse tests on bricks has been standardised by the American Society for Testing Materials. The brick is laid flatwise on two knife edges (A and B, Fig. 241) having a span of 7 inches. The load is applied through a third knife edge (C) placed at the middle of the span. Steel plates (D), ¼ inch thick,

1½ inch wide, are placed between the knife edges and the brick. The knife edges are machined approximately to a ⅜-inch radius and are slightly curved in the direction of their length. A wooden base block (E, 12 × 6 × 5 inches), slightly rounded transversely across its top, is recommended.

The modulus of rupture is calculated from the formula—

$$R = \frac{3Ws}{2bd^2}$$

where R = modulus of rupture in lbs. per square inch
W = breaking load in lbs.
s = span in inches (7 inches)
b = breadth of the brick in inches
d = depth of the brick in inches.

§ 253. **Transverse Strength of Concrete.**—No definite size has been standardised for beams for transverse tests. Withey[13] used beams, 6 × 6 inches, loaded centrally on a span of 36 inches. The results he obtained on 1 : 2 : 4 concrete mixed by volume, are given in Table LXXXIX.

TABLE LXXXIX.

	1 : 2 : 4 Concrete—Age 1 Month. Average of 25 to 27 Tests.
Tensile strength, lbs./sq. in. (S_t)	189
Compressive strength, lbs./sq. in. (S_c)	1940
Modulus of rupture, lbs./sq. in. (S_b)	352

$S_b = 0{\cdot}18\ S_c = 1{\cdot}86\ S_t$.

§ 254. **Increase of Strength of Concrete with Age.**—The average percentage of strength of concrete at different ages, assuming full strength at one year, is given in Table XC. There is no reliable data for strength of concrete more than two years old.

§ 255. **Effect of Vibration, Jigging, and Pressure on the Strength of Concrete.**—Vibration and jigging methods are useful for getting concrete into place around reinforcing bars and in intricate forms but do no good and, in some cases, are harmful if applied after the concrete is properly placed in position.

Abrams[14] finds that the vibration of an electric hammer has very little influence on the strength of puddled concrete when applied for periods not exceeding 30 seconds. If a greater time of vibration is employed there is a steady falling off in strength.

After 45 to 60 seconds the strength is only 90 per cent. of that given by the standard method of puddling.

If pressure is applied to concrete after moulding, water is expelled and a drier concrete is produced. This gives increased strength.

Abrams finds that a pressure of from 200 to 500 lbs. per square inch during moulding increases the compressive strength by 20 to 35 per cent.

TABLE XC.

VARIATION OF STRENGTH OF CONCRETE WITH AGE.

Age.	Percentage of Full Strength.
7 days	30
1 month	60
2 months	75
3 ,,	85
4 ,,	90
6 ,,	95
9 ,,	98
12 ,,	100

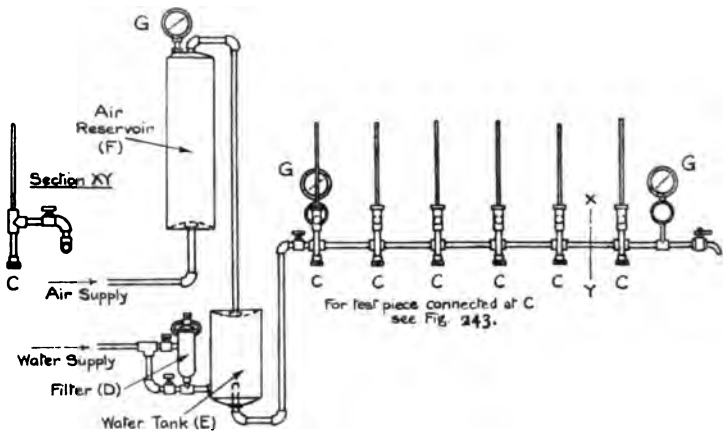

FIG. 242.—Permeability apparatus. (Measurement of water passing out of the specimen.)

§ 256. **Permeability of Concrete and Mortar.**—Permeability depends upon minute passage ways in the material which are so connected that water can flow right through. Tests under high

heads of water have been made and show that even cement paste is not absolutely impervious. Concrete and mortar can, nevertheless, be made which, under normal pressures, do not show any dampness on the outside.

Two methods of test are employed:—

(1) The amount of water passing through the material is collected and weighed.

(2) The weight of water, which has to be supplied in order

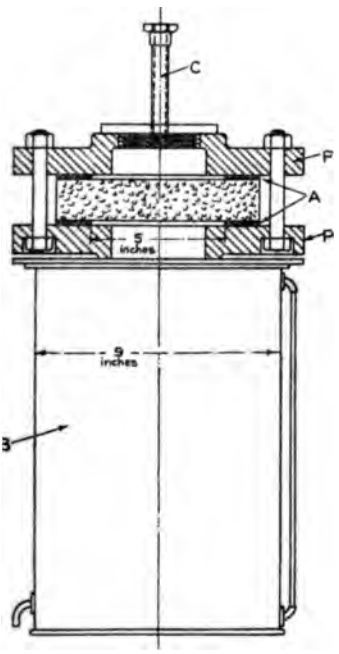

FIG. 243.—Permeability test-piece.

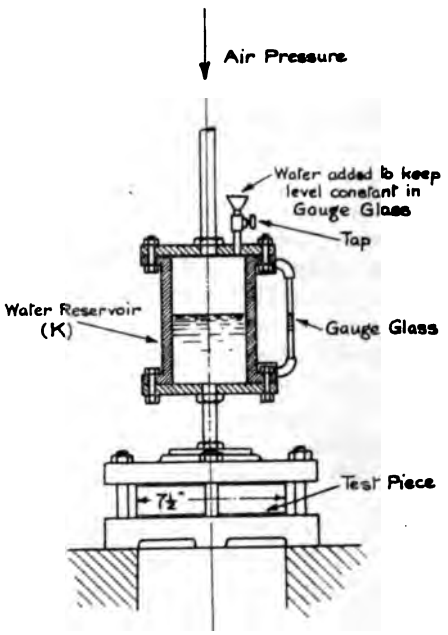

FIG. 244.—Permeability apparatus. (Measurement of the quantity of water entering the apparatus.)

to keep a constant head, is measured (i.e. the water going into the test-piece).

The arrangement of a suitable apparatus for method (1) is given in Fig. 242 and a section of the test-piece, together with the can for catching the water, in Fig. 243.

The test-piece (7½ inches diameter) has annular spaces at the outer edges of both the top and bottom surface painted with a rubber waterproofing paint. This leaves an annular piece 5 inches diameter in the original condition. Rubber washers

(AA) are placed over the waterproofing and the specimen is securely clamped between the two cast-iron plates (PP).

The water is applied to the top of the test-piece through the pipe (C) and any water passing through is caught in the can (B). The specimen is soaked in water for 48 hours immediately before the test.

The arrangement, Fig. 242, permits of six tests being carried out at once. Each test-piece with its holder is attached to a union (C). The water passes through a filter (D) and tank (E) before reaching the specimen. Air pressure is supplied to the tank (E) by a compressor, an air reservoir (F) being inserted to equalise the pressure. Three gauges (G), one on the air reservoir and two on the water pipe, are provided for reading the pressure. Readings of the quantity of water collected in the can (B) are taken at frequent intervals at the commencement of the test but the rate of percolation of water diminishes as the test proceeds, and the intervals between the readings can be reduced until it becomes constant.

In order to measure the water supplied (method 2), the arrangement is slightly modified by fitting a water reservoir (K) above the test-piece holder (Fig. 244). This reservoir is only partly full of water and the pressure is applied to the top of the water by the compressed air. The amount of water added at regular intervals, to keep the level constant in the gauge glass is recorded.

With an investigation carried out at the National Physical Laboratory on the permeability of reinforced concrete under a pressure of 8·7 lbs. per square inch, air pressure was replaced by an actual head of water of 20 feet which was kept constant by adding water to a reservoir as described for the last experiment.

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[4] Unwin, "Report of British Association," 1887, p. 879.
[5] Hannover, "Int. Assoc. Test. Mat. Proc.," 1912, Paper xxviii 7.
[6] Stanton Walker, "Amer. Soc. Test. Mat. Proc.," 1919, p. 584.
[7] Lea, F. C., "Modulus of Elasticity of Concrete," "Concrete Institute Proc.," April 28th, 1921.
[8] Lea, F. C., "British Association, Section G.," August, 1920, and "Engineering," August 27th, 1920.
[9] Henby, "Assoc. Engr. Soc. Jour.," Vol. XXV, p. 145.
[10] Mills, "Cornell Civil Engineer," Vol. XIX, p. 106.
[11] Woolson, "Engr. News," Vol. LIII, p. 561.

[12] Humphrey and Holmes, "Structural Materials Testing Laboratories at St. Louis, Mo.," Bulletin No. 329, U.S. Dept. of Geological Survey, 1908.

[13] Withey, University of Wisconsin, Bulletin No. 197.

[14] Abrams, "Effect of Vibration, Jigging and Pressure on Fresh Concrete," Structural Materials Research Laboratory, Chicago, 1919, Bulletin No. 3.

CHAPTER XXIII.

TESTING ROAD MATERIALS.

§ 257. THERE are two methods of estimating the comparative value of materials for road construction. The first is to lay sections of a road with the materials which are to be compared and observe the effect of traffic on them, and the second is to subject the road materials to laboratory tests designed to imitate actual conditions met with on the road. The former method, with great care, will give results but the process is long and costly. The use of some form of experimental road sections is, however, the only thorough method of testing asphalt carpets. Observations of the behaviour of macadam roads, constructed with rocks whose physical characteristics have been determined by laboratory tests enables these tests to be used in order to judge the probable adaptability of any rock for use in road construction.

A determination of the relative road building qualities of different types of rock was first systematically attempted in France. The French School of Bridges and Roads installed a road materials laboratory in 1878 and it was there that the Deval[1] attrition machine was designed and its excellence has led to its general adoption as a standard testing machine.

The testing of road metal was initiated in Germany in 1884 at the first Munich Conference for Establishing Uniform Conditions of Testing. They appointed a committee to draft the methods of testing that were necessary, the work performed by this committee was reported to conferences held in 1886, 1890, and 1893, and definite proposals for testing, including the Deval test, were submitted and approved.

In 1893 Massachusetts Highway Commission[2] founded a laboratory for testing road materials in the Lawrence Scientific School of Harvard University. In 1900 the United States Government, because of the growing importance of road material investigations, established a laboratory in the Bureau of Chemistry

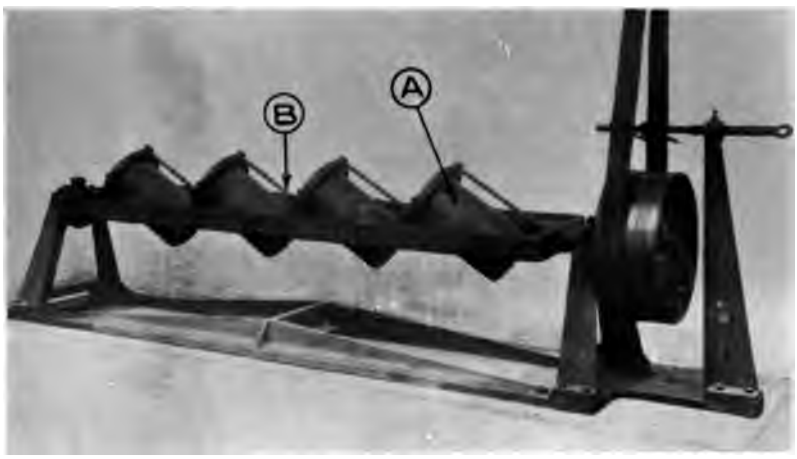

FIG. 245.—Deval attrition machine.

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of the Department of Agriculture. This laboratory, transferred in 1905 to the Office of Public Roads, examines, without charge, samples of road material submitted by any citizen of the United States.

The only stone testing appliance believed to be in existence in England prior to 1911 was the "Rattler" attrition machine designed and used by E. J. Lovegrove,[3] Borough Engineer and Surveyor of Hornsey.

In 1911 a Road Laboratory was inaugurated as a Division of the Engineering Department of the N.P.L., Teddington, in accordance with a scheme drawn up by the Road Board and approved by the Treasury. The work of the Road Board has now been taken over by The Ministry of Transport (Roads Department).

In order to preserve continuity with the work which has been in progress in other countries standard types of machines, as used by The United States Office of Public Roads, were adopted.

§ 258. **Attrition Test.**—The machine used for this test is of the four-cylinder Deval type which has given satisfactory results in France since 1878. It is shown in Fig. 245 and consists essentially of four cylinders (A), $7\frac{1}{2}$ inches in diameter and 14 inches long, mounted on a frame (B) in such a way that their axes are inclined at 30° to the axis of rotation.

Eleven lbs. of rock, numbering as nearly fifty pieces as possible, are placed in one of the cylinders, the cover bolted on, and the machine revolved 10,000 times at a rate of about 30 revolutions per minute. The dimensions of the stones should be such that every stone will pass through a $2\frac{1}{2}$-inch ring, but will fail to pass through a 2-inch ring. Only the material worn off which will pass a sieve of $\frac{1}{16}$-inch mesh is considered in determining the amount of wear. This amount is expressed as a percentage of the 11 lbs. used. In addition the French coefficient which is in general use is calculated. This is defined by the relation—

$$\text{French coefficient of wear} = \frac{40}{\text{percentage of wear}}.$$

A wet test is also made, and for this purpose 1·1 gallons of water are placed with the 11 lbs. of stone. With the majority of stones it is found that there is more wear under a wet test than under the dry test, but occasionally the reverse is the case.

An approximate relation has been established between this machine and Lovegrove's "Hornsey Rattler".

If x = percentage of wear with the Deval machine (dry)
y = " " " " " " (wet)
x_1 = " " " Lovegrove machine (dry)
y_1 = " " " " " (wet)

Then $$\frac{40}{x} = \frac{75}{x_1} + 5 \text{ and } \frac{40}{y} = \frac{155}{y_1}.$$

§ 259. **Repeated Blow Impact (Toughness Test).**—(1) *Preparation of Specimen.*—The specimen is prepared in the form of a cylinder 1 inch diameter by 1 inch long. A piece of the rock is roughly chiselled to size $1\frac{1}{4} \times 1\frac{1}{4} \times 3$ inches. It is ground approximately cylindrical on a large crystolon wheel and then placed in the chuck of a grinding machine where it is ground by a small crystolon wheel to exactly 1 inch in diameter. The chuck and stone are then taken to the diamond saw (Fig. 246) where the specimen is cut off 1 inch in length.

(2) *The Testing Machine.*—The machine used for this test is known as the Page Impact machine (Fig. 247). The blow is given by a 4·4 lbs. hammer (H) and acts through a plunger (P) whose surface of contact with the specimen is spherical and has a radius of 0·4 inch. The blow, as thus delivered, approximates to the blows of traffic and the spherical end has the further advantage of not requiring great exactness in getting the two bearing surfaces of the test-piece parallel; the entire load being applied at one point on the upper surface. The test consists of a 0·4 inch fall of the hammer for the first blow, and an increased fall of 0·4 inch for each succeeding blow until failure of the specimen occurs. The number of blows required to destroy the test-piece is used to represent the toughness.

A roller chain (C) driven from the shafting is supported on sprocket wheels attached to castings at the top and near to the base of the machine. The chain is provided with small lugs which engage a spring bolt attachment (B) projecting inwards from the top of the hammer. This raises the hammer until the latter is tripped by a rod (R) projecting downwards from a cross-head which slides on two rods connecting the upper and lower castings. The cross-head is raised automatically through 0·4 inch after every blow by a lead screw driven by a worm and worm-wheel (S) attached to the same shaft as the upper sprocket wheel. By throwing the lead screw out of gear with the cross-head the latter can be raised or lowered through any desired height, or the test can be made with a constant height of fall.

A slightly different method of preparing the test sample is

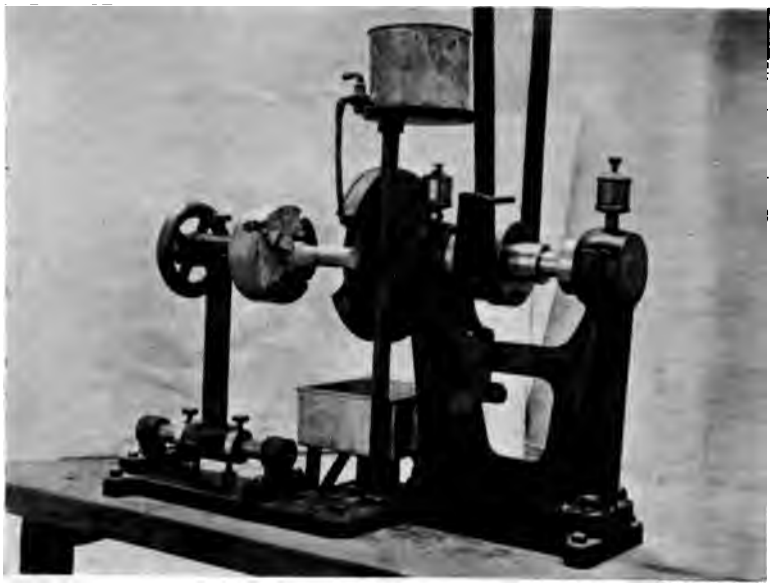

FIG. 246.—The diamond saw.

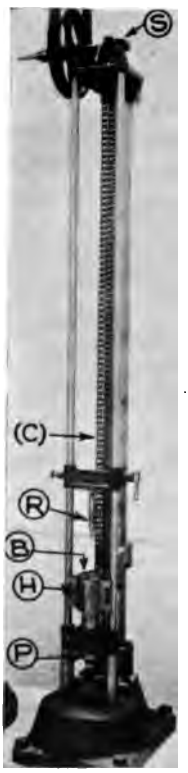

FIG. 247.—Repeated blow impact machine.

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FIG. 248.—Dorry abrasion (or hardness) machine.

FIG. 249.—The ball mill.

[To face p. 379.

sometimes employed, viz. by the use of a core drill. This consists of a brass core tube having at its lower end a steel ring containing eight small diamonds in its cutting edge, four on the outer edge and four on the inner edge. The drill arranged to cut a rock core 1 inch diameter runs at 200 to 300 revolutions per minute. Water is supplied to the inside of the drill and the specimen through a stationary brass ring by a rubber tube connection.

§ 260. **Abrasion Test.**—The specimen is prepared in the same manner as that for the repeated blow impact test, and in cases where both tests are required the specimens can usually be both cut from the same sample.

The machine used (sometimes called a Hardness machine) is of the "Dorry" type (Fig. 248) and consists of a circular cast steel disc which revolves in a horizontal plane about a vertical shaft. The specimen is held with its axis vertical and its lower end pressed with a force of 3·5 lbs. per square inch against the surface of the disc. Standard sand, 30 to 40 mesh, is fed continuously upon the disc through funnels, and it is important that an even and constant supply of the abrading material should be fed to each sample tested. After 1000 revolutions of the grinding disc, revolving at the rate of about 28 revolutions per minute, the loss of weight of the specimen is found. The test is repeated with the specimen reversed and the average loss of weight computed from the two runs is used in determining the hardness.

This is given by, $H = 20 - \frac{1}{3}W$ where H is the hardness number or coefficient of wear and W is the loss in grammes per 1000 revolutions.

§ 261. **Cementation Test.**—The cementing value of a rock dust measures the ability of that dust to hold the individual particles together to form a firm impervious road surface.

The process involved in making a test of the cementation value of a rock are as follows:—

(*a*) Grinding up a mixture of the rock, coarsely crushed, and water into a stiff paste in a ball mill.

(*b*) Forming briquettes from this paste in a mould under pressure, which are dried after twenty-four hours.

(*c*) Subjecting each briquette to repeated blows with a small hammer, and measuring automatically the recoil of the hammer after each blow.

(1) *Ball Mill* (Fig. 249).—1·1 lb. of coarsely crushed rock and 0·02 gallon of water are placed in the mill together with two steel shots each 5·1 inches in diameter. The samples are ground in this mill for two and a half hours the mill revolving at

the rate of 2000 revolutions per hour. The resulting paste is then ready to be moulded into briquettes.

(2) *Briquette Machine* (Fig. 250).—The paste is placed in a mould, and a cylindrical plug screwed upon it. The mould is in contact with the short arm of a weighted beam, so that the pressure can be regulated to give a maximum value of 1880 lbs. per square inch. The size of the briquette is 1 inch diameter and 1 inch long.

(3) *Repeated Impact Machine* (Fig. 251).—After drying for twenty hours in air and four hours in a hot air bath at 200° F., the briquette is allowed to cool for twenty minutes in a desiccator, it is then placed on the anvil of the machine with its axis vertical. A small hammer (H) is operated by a cam (C), so that the effective drop is always 0·4 inch, and the force of the blow is transmitted to the specimen by means of a plunger (P) working in a vertical guide. This plunger is also connected to the arm of a lever, the other end of which carries a pencil in contact with paper on a revolving drum (D), so that any rebound of the plunger after the blow is indicated on the paper. In this way a diagram is obtained which will give the number of blows after which there is no rebound of the plunger, i.e. after which the resilience of the specimen is destroyed. Six specimens are made from each sample and the average result is taken as a measure of the cementing value of the material.

Table XCI gives the interpretation of the results from the physical test on road stones.

Particulars of tests carried out in the U.S.A. are given by Blanchard.[4]

§ 262. **Petrological and Geological Characteristics.**—Thin sections are cut from the stone and examined under the microscope to ascertain the nature, quantity and dimensions of the components which form the stone and determine the correct petrological designation of the material.

§ 263. **Further Tests.**—Specific gravity, absorption of water, crushing, sand blast abrasion and paving brick rattler tests are carried out in the manner previously described for stones, bricks and concrete (Chapter XXII). It is usual, however, when dealing with road stones to make the crushing tests on cylinders 1 inch or 2 inches diameter with the length equal to the diameter. The crushing test-pieces, when 1 inch diameter, are identical with those for impact and abrasion tests and can be made with the same apparatus.

§ 264. **Endurance Tests on Model Roads.**—It was recognised that in the case of the various test trial roads laid down

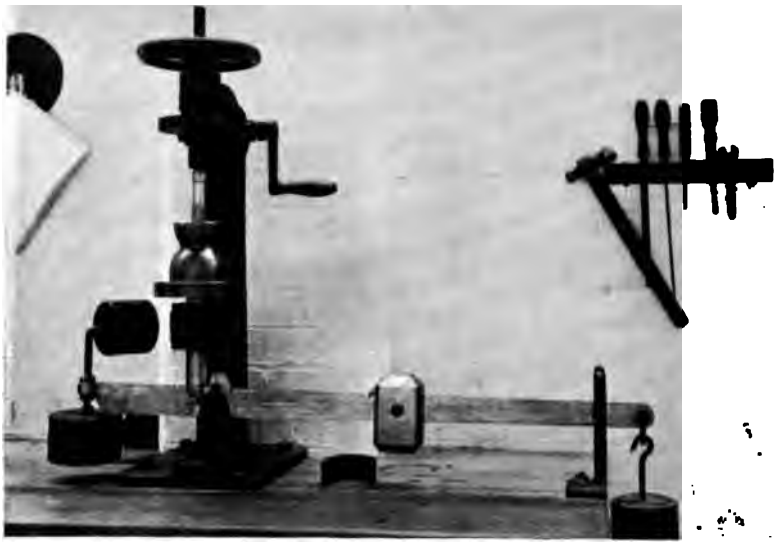

FIG. 250.—Machine for making briquettes.

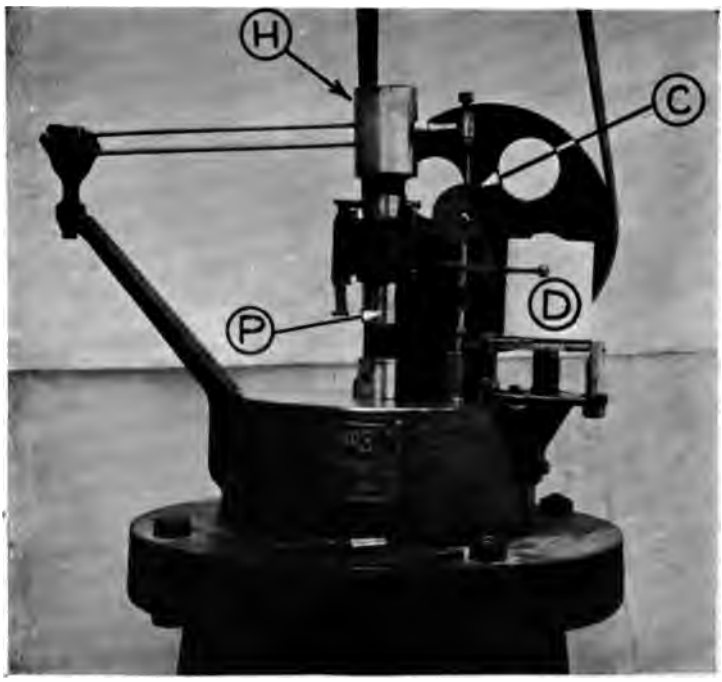

FIG. 251.—Repeated impact machine for cementation tests.

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TABLE XCI.

INTERPRETATION OF THE PHYSICAL TESTS ON ROAD STONES.

	Attrition Test. Per Cent. of Wear.		Impact Test. No. of Blows for Failure.	Abrasion Test. Coefficient of Wear.	Cementation Value. No. of Blows for Failure	Absorption of Water. Lbs. per Cub. Ft.	Crushing Strength. Lbs. per Sq. In.
	Dry.	Wet.					
Very good . . .	2 and under	2 and under	19 and over	19 and over	Over 100	0·10 and under	Over 20,000
Good	2·1 to 2·5	2·1 to 3·1	16 to 18	17 to 18·9	76 to 100	0·11 to 0·40	15,000 to 20,000
Fairly good . . .	2·6 ,, 3·1	3·2 ,, 4·0	13 ,, 15	16 ,, 16·9	26 ,, 75	0·41 ,, 1·00	10,000 ,, 15,000
Rather poor . . .	3·2 ,, 4·0	4·1 ,, 5·0	8 ,, 12	15 ,, 15·9	10 ,, 25	1·01 ,, 3·00	5000 ,, 10,000
Very poor . . .	Over 4·0	Over 5·0	Under 8	Under 15	Under 10	Over 3·00	Under 5000

in this country, such as those at Sidcup, the best method of road construction would not show measurable wear or deformation until after years of heavy traffic. At the suggestion of Col. Crompton a model road-testing machine was designed at the National Physical Laboratory in order to provide a more rapid method of comparing the efficiency of methods of construction. This design was approved by the Road Board and its construction commenced in 1912, the first run taking place in 1913. The machine (Fig. 252) consists of a circular track 30 inches wide having a mean diameter of 34 feet. The endurance of the centre 24 inches of this track is tested by the rolling on it of eight steel-tyred wheels, 3 inches wide and 39 inches diameter. The wheels are at an angular distance of 45° from each other, and each wheel is rotated by a separate electric motor mounted on a steel arm which revolves round a centre post. The radial distribution of the wheels is such that the whole width of 24 inches is covered in one revolution of the arms, and in order to prevent as far as possible the formation of ruts in the tested surface each wheel is moved backwards and forwards radially by a cam mechanism through a distance of 1 inch. The eight arms are all hinged to a rotating boss on the centre post, and at their outer ends are connected by spiral springs to eight corresponding cantilevers rigidly fixed to a second rotating boss connected with the former and immediately below it. The pressure of each wheel on the track can be adjusted to any desired value up to 25 cwt.

In most cases the weight per inch of tyre is 450 lbs. but during the consolidation stage this is sometimes increased to 750 lbs., which is approximately the maximum allowed by the Local Government Board regulations.

The test is carried out in the following manner: The hot material is filled into the track, then levelled by raking to the depth required to consolidate it to a finished carpet 1½ inch thick, the consolidation is carried out by rolling it with the machine, by hand rolling and tamping, or by floating, as makers prefer.

At the time the track is made test samples are made in different moulds and preserved for reference. The machine is then started and run on the new surface with a gradually increasing load until about 6000 tons per yard width have rolled over it—this is called the consolidation period.

For the test proper the machine is run at a load of 470 lbs. per inch of width of tyre and at a rate of about 2200 tons per yard width of the road surface per hour, the track being kept wet

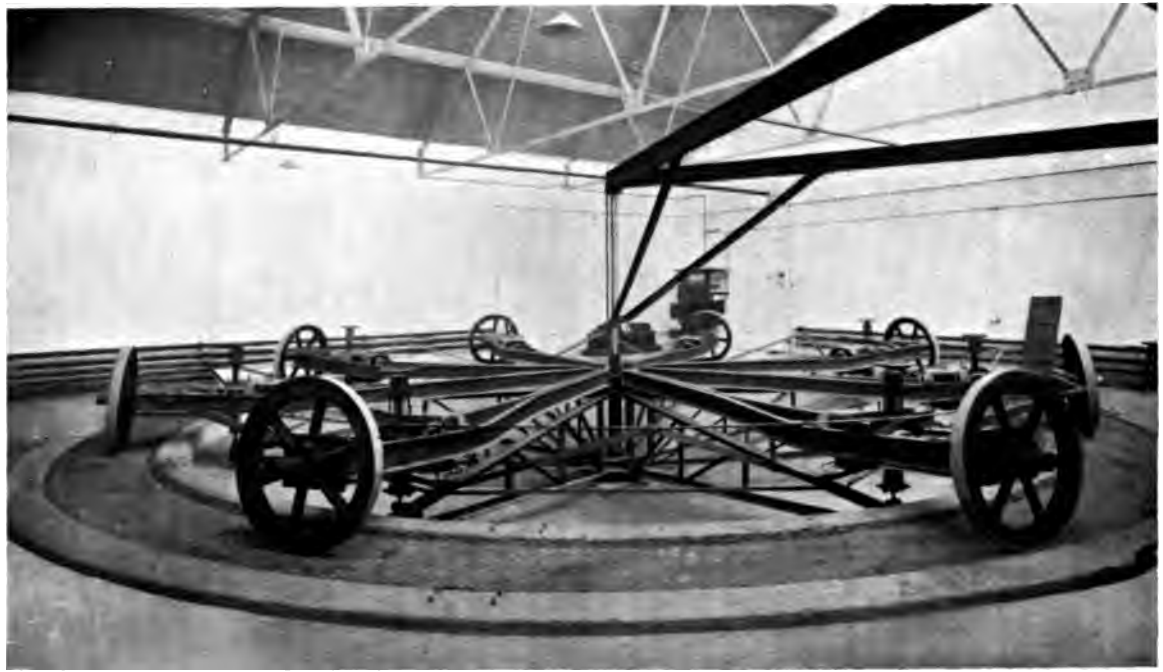

FIG. 252.—Road testing machine.

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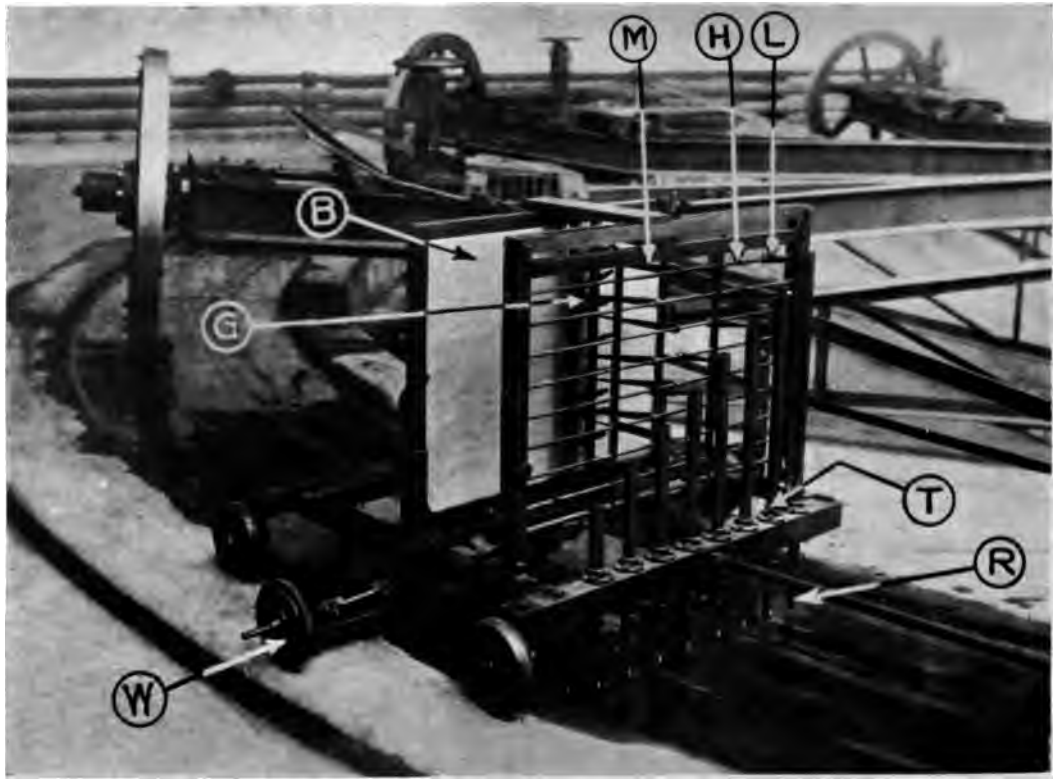

FIG. 253.—Apparatus for drawing longitudinal and cross sections of the test road.

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all the time. The condition of the track is observed periodically and any defects which may appear are recorded.

The results obtained show that upwards of 400,000 tons per yard of width can be obtained before the vibration caused and communicated to the building is excessive. The figures obtained on the machine must always be regarded as relative and not as indicating the weight of traffic which the materials will carry when laid on the road.

In order to investigate the question of the formation of waves a special apparatus has been constructed for drawing cross sections of the road at different points round the track and longitudinal sections at the centre of the tracks of the eight rotating test wheels.

The ordinates of the longitudinal sections of the road are obtained by eight small rollers (R, Fig. 253) which follow the tracks of the eight wheels. Each roller is attached to a rod guided in a brass tube (T) and is kept on to the road surface by means of a spring.

A lever (L), with a ball end, rests on the roller rod, and is fixed to a horizontal rod (H) supported on centres. This horizontal rod is thus free to rotate. A vertical movement of the small roller causes its lever to rotate the horizontal rod. This rotation is communicated to a further lever (M) with a ball end which moves a pen vertically in a guide (G).

The paper on which the record is obtained is fixed on a board (B). This board is moved by a screw driven through a flexible coupling by a wheel (W) resting on the wall at the side of the road. A curve is drawn on the paper as the instrument is pulled round the track. The horizontal scale is such that the length of the track (107 feet) is represented by 22 inches, while the depths of the hollows are exaggerated in the ratio of 2 to 1. A hollow ½ inch deep shows as 1 inch on the record.

By stopping the apparatus at any point, a cross section of the track can be drawn on paper fixed on the other side of the board. This is done by pulling a roller across the track. The frame carrying the roller is put in gear with the board which moves half the distance of the roller, thus a length of cross section of 24 inches is shown on the record by 12 inches. The recording pen is worked vertically by an arrangement of levers similar to that described for the longitudinal sections.

Plaster casts are also taken to obtain a permanent record of the appearance of the road at various stages during the test.

It has been found that a road becomes too bad for use in three ways :—

(1) By excessive wave formation.

(2) By disintegration.

(3) By a combination of disintegration and excessive wave formation.

The formation of waves is increased by the road being subjected to heavy traffic after insufficient or unequal consolidation, while disintegration occurs rapidly with change of climatic conditions, if the road consists partly of small or large stones when these stones are brought to the surface by deformation or wear.

A summary of the more important tests carried out with this apparatus is given in the Sixth Annual Report of the Road Board (1916).

§ 265. **Bituminous Materials.**—The physical character of bituminous binders and aggregates is determined by micro-sections, penetrometer and viscosimeter determinations, quantity and quality of the contained bitumen (whether natural or artificial) and the physical and chemical examination of the residue.

Methods of carrying out these tests are fully described by Hubbard.[5]

REFERENCES FOR CHAPTER XXIII.

[1] Deval, "Ann. des ponts et chaussées," 1879, and "Bulletin du Ministere des Travaux publics," 1881.

[2] "Bulletin No. 44 on Physical Testing of Rocks for Road Building, U.S. Department of Agriculture."

[3] Lovegrove, Flett and Howe, "Road-making Stones, Attrition Tests in the Light of Petrology," 1910, The St. Bride's Press, Ltd.

[4] Blanchard, "American Highway Engineers' Handbook," 1919, Chapman & Hall, Ltd.

[5] Hubbard, "Laboratory Manual of Bituminous Materials," 1916, Chapman & Hall, Ltd., and "Highway Inspectors' Handbook," 1919, Chapman & Hall, Ltd.

CHAPTER XXIV.

LIMES AND CEMENTS.

§ 266. THE cementing materials ordinarily used in engineering construction are classified as follows:—

(1) Gypsum Plasters.

(2) Limes: Quicklime, Hydrated Lime, Hydraulic Lime.

(3) Cements (Hydraulic).

§ 267. **Gypsum Plasters.**—In plaster of Paris, Keene's cement, stucco, etc., the essential constituent is gypsum in a more or less dehydrated state.

Gypsum in its native state is crushed and ground, and then calcined at a temperature of 200° C. The product is then finely ground and screened.

Plaster of Paris is produced when the gypsum is not completely dehydrated. The theoretical composition of gypsum is $CaSO_4 + 2H_2O$ (a hydrous calcium sulphate). Plaster of Paris has the approximate composition of $CaSO_4 + 0{\cdot}5H_2O$.

The specific gravity of gypsum is 2·3, of plaster of Paris 2·57, and of completely dehydrated gypsum it is 2·95.

Keene's cement is practically pure calcium sulphate with a small percentage of calcium carbonate ($CaCO_3$). For the manufacture of this cement the gypsum is procured in as pure a state as possible and the resulting product is of an exceptionally pure white colour. The small percentage of $CaCO_3$ is introduced by dipping the calcined gypsum into a solution of alum and then burning again. The introduction of this "impurity" produces a slow setting cement which ultimately becomes very hard.

Cement plaster and stucco are calcium sulphates with adulterants which retard setting and increase plasticity.

§ 268. **Limes.**—Pure lime (quicklime) is produced by the calcination of nearly pure limestone, at a temperature of about 500° C., in some form of vertical kiln. By this process the carbon dioxide is driven off from the calcium carbonate ($CaO \pm CO_2 = CaCO_3$). Such limes slake violently on the

addition of water, form calcium hydroxide ($Ca(OH)_2$) and increase in volume by about 300 per cent. They harden slowly by absorbing carbon dioxide from the air.

Poor limes have a high percentage of magnesia and slake more slowly.

Owing to the fact that quicklime is insufficiently slaked or mixed in many cases when this is done on the job, this process is sometimes carried out in especially designed and equipped plant where the operations are conducted more efficiently and with the minimum quantity of water. The resulting product is thoroughly screened and ground and is known as hydrated lime.

Pure hydrated lime should have a specific gravity of 2·08. It is usually tested by chemical analysis, for fineness and soundness and sometimes for tensile or compressive strength in the manner presently to be described for Portland cement.

Hydraulic Lime.—John Smeaton discovered that limestone containing a small percentage of clay, when calcined, produces a lime which hardens by chemical action apart from the absorption of carbon dioxide from the air. This lime slakes in the usual way and, in addition, hardens under water; it is therefore called hydraulic lime.

§ 269. **Hydraulic Cements**, of which the best example is Portland cement, are produced by the calcination of chalk and clay or suitable limestone and shales.

In various parts of the world there are deposits in which the mixing of these materials has been carried out by nature. The result of calcination of these natural deposits produces a natural hydraulic cement. The natural rock contains as a rule an excess of carbonate of lime rendering the resulting cement poor in quality.

Portland cement is an artificially produced cement in which the chalk and clay are accurately proportioned and thoroughly mixed together before burning to a hard clinker at a temperature of about 750-800° C. The clinker is then ground and forms the final Portland cement. A finely ground cement makes a stronger mortar than a coarsely ground one hence the fineness of the cement is a property which it is necessary to specify.

Portland cement is a British invention. It was discovered by Joseph Aspdin in 1824 and owes its name to its resemblance, when set hard, to Portland stone. It sets rapidly, sets under water and hardens slowly with but little change in volume until it is nearly as strong as stone. The hydraulic property is due to the presence of silicate of alumina.

The British Engineering Standards Association, in their standard specification (No. 12, see Appendix), define Portland cement as follows: "The cement shall be manufactured by intimately mixing together calcareous and argillaceous materials, burning them at a clinkering temperature and grinding the resulting clinker".

Cementing materials are subject to large variations in the quality. It is necessary, therefore, to closely control the manufacture by imposing tests to ensure that the properties which it has been found are of first importance should reach a specified standard.

The main properties required in a cement are strength, permanence, and time of setting suitable to the work.

The principal tests which are in general use to determine the suitability of the cement for fulfilling those requirements are :—

(*a*) Fineness of grinding.
(*b*) Specific gravity.
(*c*) Chemical composition.
(*d*) Strength.
(*e*) Time of set.
(*f*) Soundness or constancy of volume.

In order to obtain uniformity in the testing results it is necessary that the conditions of test should be exactly the same in each case and that the personal element should be, as far as possible, eliminated.

This has been provided for in the various specifications for Portland cement, such as those by the British Engineering Standards Association [1] (B.E.S.A.) or the American Society of Testing Materials [2] (A.S.T.M.), in which standard methods for carrying out the tests are described in detail.

§ 270. **Sampling.**—It is important that (1) the sample is representative of the whole consignment, (2) a sufficiently large sample is secured to carry out, in duplicate, all the tests required, (3) the storage of the sample is such that the quality of the cement is not affected before the tests are made, and (4) the sample is properly mixed, if it is obtained from various parts of the consignment.

Eight pounds of cement are usually sufficient for a sample. The B.E.S.A. specify that each sample shall consist of equal portions selected from twelve different positions in the heaps, bags or barrels. Samples are usually stored in airtight tins.

§ 271. **Fineness Tests.**—The fineness of cement for specification purposes is determined by means of the weight of residue

(as a percentage of the original weight of the sample) which is left on a sieve after a definite period of sifting. The B.E.S.A.[1] and the A.S.T.M.[2] specify that the wire of the sieves shall be woven (not twilled) and that the ... to be mounted on frames without distortion. The sizes adopted are slightly different in the two specifications. Particulars are given in Table XCII.

TABLE XCII.

FINENESS TEST.

	B.E.S.A. Specification.		A.S.T.M. Specification.
Size of sieve, wires per inch.	180 × 180	76 × 76	200 × 200
Diameter of wire, inches .	0·0018	0·0044	0·0021
Residue shall not exceed .	14 per cent.	1 per cent.	22 per cent.
Weight of sample, grammes	100 grammes		50 grammes
Time of continuous sifting .	15 minutes on each sieve		Until not more than 0·05 grammes passes through in one minute

Mechanical shakers are sometimes employed in laboratories where a large amount of work has to be carried out. They are not recommended as very little time is saved as compared with efficient hand sifting and the results are not so consistent.

It is usually considered that the size of the very fine flour of Portland cement cannot be obtained by the use of sieves. For separating very fine powders air separators are often used. These are fully described in the Proceedings of the International Association of Testing Materials for 1912.

Abrams,[3] as a result of a series of experiments on the effect of fineness of cement on the strength of concrete, finds that :—

(1) In general the strength of concrete increases with the fineness of a given lot of cement but there is no necessary relation between the strength of concrete and the fineness of cement if different cements are used.

(2) Fine grinding shortens the setting time, is more effective in increasing the strength of lean mixtures than rich ones, and increases the strength of concrete more at seven days than at times from one to twelve months, i.e. fine grinding expedites the hardening of the concrete.

(3) If the mixture is "wet" the rate of increase of strength, due to greater fineness, is lowered.

§ 272. **Specific Gravity.**—The weight of cement or its "apparent" density, decreases with fineness, i.e. a cement

coarsely ground gives a heavier weight per cubic foot than the same ... round finely. The "apparent" density of cements is only a comparison of their "real" densities or specific gravities when the cements are of the same degree of fineness.

The specific gravity of cement is lowered by adulteration, hydration or underburning. The differences in the specific gravity are usually so small that it is necessary to exercise great care in making the determination.

The specific gravity of cement should not be less than 3·10. The method of determination which is recommended is by means of a specific gravity bottle. This is a volumenometer in which the liquid used is benzine, petroleum or paraffin which has been freed from water by standing over quicklime (water causes hydration of the cement and therefore an alteration of volume).

The Specific Gravity test has been deleted from the B.E.S.A. specification since August 1920.

§ 3. **Chemical Composition.**—The chemical analysis is not so important as the physical tests on cement. It, however, gives valuable indications in the detection of adulteration with considerable amounts of inert material such as slag or ground limestone. It is also used to determine whether magnesia and sulphuric anhydride are present in excessive quantities.

§ 274. **Strength Tests.**—A finely ground cement will take a certain amount of inert material without reduction of strength therefore a coarsely ground cement will give as high a strength as a finely ground one when the test-pieces are made with neat cement. As cement is seldom used neat, a strength test on the neat material is no criterion of its strength when used in practice, it, however, gives information regarding the time of setting and the soundness. Tests on briquettes made with cement and sand (usually 1 : 3 by weight) are consequently specified as a rule in addition to those on neat cement.

Cement is never used in tension, yet tensile tests are generally carried out in order to give an indication of strength. This is chiefly on account of their simplicity, rapidity and cheapness. There is, however, a tendency in some countries for compression tests to be substituted for the hitherto universally adopted tensile method. It is to be noted that the recent strength tests by Abrams [1] on fineness of cement, already referred to (§ 271), were made on concrete test-pieces in compression.

§ 275. **Tensile Strength.**—Test-pieces used for tensile tests are moulded into the form shown in Fig. 254, which represents

the briquette standardised by the B.E.S.A. The difference between this and the A.S.T.M. standard are only slight.

The form of briquette has a considerable influence on the results. Coker [4] found that the ratio of the maximum stress to the mean stress with the B.E.S.A. briquette is 1·75 (approximately), while the American and Continental forms give a value of 1·70 and 1·95 respectively. The intensity of stress is greatest along the sides of the minimum section and least at the centre.

Either single or gang moulds (see Fig. 255) are used for preparing the test-pieces. The latter permits a number of briquettes to be moulded at one time and are preferred by many laboratories since the greater quantity of material that can be mixed tends to produce more uniform results.

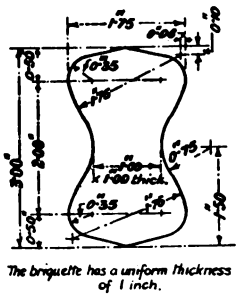

FIG. 254.—B.E.S.A. standard briquette for cement testing.

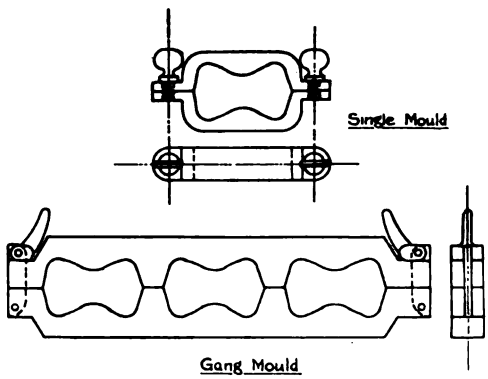

FIG. 255.—Moulds for cement testing.

§ 276. **Neat Cement Tensile Tests.**—The quantity of water used in gauging has a considerable influence on the strength of the briquette and should be such that the mixture is plastic when filled into the moulds. The amount of water varies with different cements and it is usual to make trial experiments to find the exact amount of water that is necessary. This varies from 18 to 25 per cent. by weight of the cement.

The moulds during filling rest on slate or some form of non-porous plates. They are filled by using the blade of an ordinary 7½-oz. gauging trowel, and it is usual to specify that no ramming or tamping is permitted.

The temperature of the room and of the mixing water should be as near to 16° C. as it is practicable to maintain it.

The briquettes are kept in their moulds, in a damp atmosphere

to prevent them from drying out, for twenty-four hours after gauging. For this purpose a moist chamber is a great convenience and improvement over the method of covering the test-pieces with a damp cloth which is liable to dry out unequally. A moist chamber consists of a slate, concrete or metal-lined wooden box covered inside with felt which is kept wet. The bottom of the box is arranged so as to hold water, and glass shelves for holding the briquettes rest on cleats fixed to the sides of the box.

After the expiration of twenty-four hours the briquettes are removed from their moulds and immersed in fresh water maintained at a temperature of 16° C. This water is renewed every seven days and the briquettes are left in water until required for testing.

The strength of cement increases considerably with time from setting, consequently the age at which the test-pieces are to be broken is specified. The B.E.S.A. specify that six briquettes are to be broken at seven days and six at twenty-eight days after setting, and that the breaking strength shall not be less than 450 lbs. per square inch at seven days, or $x + \frac{40{,}000}{x}$ lbs. per square inch at twenty-eight days where x = the actual strength in lbs. per square inch at seven days.

The rate of loading has a marked effect on the strength of the briquettes. The latter increases with the rapidity of loading, which has therefore to be standardised. The B.E.S.A. specify a rate of 500 lbs. per minute while the A.S.T.M. adopt 600 lbs. per minute. A variation from these rates of 100 lbs. per minute introduces an error of about 2 per cent.

The form of jaws used for gripping the test-piece is shown in Fig. 256. The load must be applied without shock and care should be observed to see that projecting edges are removed from the specimens to ensure that the briquettes are properly centred in the clips. A deviation of 0·062 inch from correct alignment will decrease the tensile strength from 15 to 20 per cent.

Tension tests of cement briquettes are generally made in small lever-testing machines of various types in which provision is made for applying the load at a steady and definite rate.

Messrs. Adie, London, supply a machine in which the load is applied by a regulated travelling poise. The poise is pulled along the beam by means of a suspended weight. The speed at which the weight descends and, therefore, that the poise travels along the beam is regulated by the cock in the plunger of a dash

pot. The plunger is attached, through the poise, to the suspended weight by an arrangement of cords and pulleys.

In the Bailey and Reid patent cement tester a cylindrical cistern is hung at the end of the single lever of the testing machine. A small stream of water is allowed to flow into this cistern enabling the load to be applied in a gradual and almost imperceptible manner. The height of the water in the cistern is indicated by means of a glass tube similar to the gauge glass of a steam boiler, and the graduations, shown on the outside, indicate the load in lbs. A small trigger automatically closes the water tap when the material is broken.

A further method of applying the load is indicated in the machine shown in Fig. 256. This is a compound lever machine with the load applied by lead shot. The briquette is held between the jaws (A), the lower jaw being attached to a straining screw (S), by means of which the lever (L) is raised into position between the stops. The load is applied by running lead shot from the container (G), through a channel (H), into the bucket (C) which is hung on to the end of the lever.

The flow of the shot is so arranged that the strain is applied to the specimen at a uniform rate of increase of 100 lbs. in twelve seconds as required for the B.E.S.A. specification. When the specimen fractures, the shot is automatically cut off by a trigger operated by the fall of the steelyard.

This machine also acts as a weighing machine for the lead shot. The container, after the test, is suspended from the back knife edge of the steelyard, the graduations traversed by the poise, along with the supplementary loose weights, represents the breaking load of the specimen. The machine is supplied by W. & T. Avery, Ltd.

§ 277. **Mortar (Cement and Sand) Tensile Tests.**— Thoroughly washed and dried sand (obtained from Leighton Buzzard in Great Britain), which will pass a 20 × 20 mesh sieve but not a 30 × 30 mesh sieve, is used for tests in which sand is required. The wires for the sieves are 0·0164 and 0·0108 inch in diameter respectively.

The cement and sand are mixed in the proportion of 1 : 3 by weight for the standard test-pieces, about $1\frac{1}{4}$ lbs. of cement and $3\frac{3}{4}$ lbs. of sand will make twelve briquettes. The gauging must be made without any excess of water being present. The quantity of water is approximately 10 per cent. of the united weights of the sand and cement, the exact quantity required should be determined by a trial mixing.

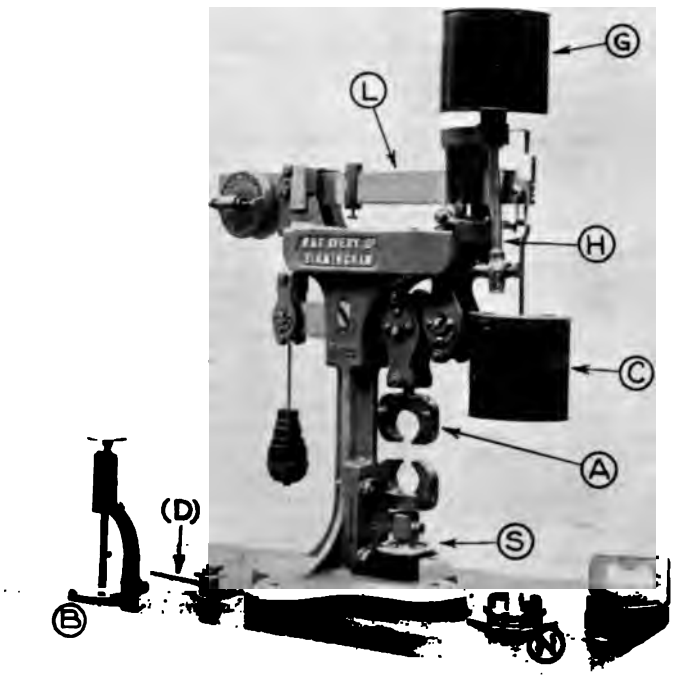

FIG. 256.—Cement testing machine.

[*To face p.* 392.

The gauging is carried out on some form of non-absorbing surface, preferably glass, with a room temperature and water temperature of 16° C.

The method of filling is described by the B.E.S.A. specification as follows:—

"The mixture gauged as above shall be evenly distributed in moulds of the form required, each mould resting upon a non-porous plate. After filling a mould a small heap of the mixture shall be placed upon that in the mould and patted down with the standard spatula until the mixture is level with the top of the mould. This last operation shall be repeated a second time and the mixture patted down until water appears on the surface; the flat only of the standard spatula is to be used and no other instrument or apparatus is to be employed for this operation. The mould after being filled may be shaken to the extent

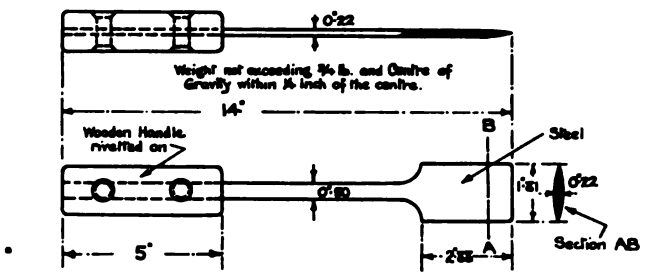

FIG. 257.—B.E.S.A. standard spatula for cement tests.

necessary for expelling the air. No ramming or hammering in any form will be permitted during the preparation of the briquettes, which shall then be finished off in the moulds by smoothing the surface with the blade of a trowel." The standard spatula is shown in Fig. 257.

Various types of moulding and mixing machines have been devised and are in use in some countries. They are, however, not allowed by the B.E.S.A. specification. Mechanically moulded briquettes give greater strength than hand moulded ones.

Mortar briquettes are stored in moist air for twenty-four hours and then in water (at 16° C.) until required for testing. They should be broken as soon as possible after being taken out of the water and should never be allowed to dry. The B.E.S.A. specify that six briquettes are broken after periods of seven and twenty-eight days, at a uniform rate of loading of 500 lbs. per minute

(600 lbs. per minute in the U.S.A.). The strength should not be less than 200 lbs. per square inch at seven days after gauging, or $x + \frac{10{,}000}{x}$ lbs. per square inch twenty-eight days after gauging, where x = the actual strength at seven days in lbs. per square inch.

§ 278. **Characteristic Equations for Tensions Tests.**—Unwin [6] has found that the rate of hardening of cement and cement and sand briquettes follows, very approximately, a simple law.

If y = the strength of the briquette in lbs. per square inch at x weeks after gauging, and a, b and n are empirical constants,

Unwin found that $y = a + bx^n$.

n is constant for one cement and if a be taken as the initial strength after one week

$$y = a + b(x - 1)^n.$$

For tension briquettes the gain of strength is nearly proportional to the cube root of the time of hardening.

Thus for Portland cement in tension $n = \frac{1}{3}$

and $y = a + b\sqrt[3]{x - 1}$

where a = the initial strength (at seven days)

b = a constant varying with the rate of increase with time.

These two constants give a clear indication of the character of the cement.

In the B.E.S.A. specification for neat cement briquettes, where the lowest value which is accepted for "a" is 450 lbs. per square inch, the minimum value for "y" (4 weeks after gauging) is

$$= 450 + \frac{40{,}000}{450} = 539$$

$$y = a + b\sqrt[3]{x - 1} \qquad \text{and where } x = 4$$

$$539 = 450 + b\sqrt[3]{4 - 1}$$

therefore $b = 61{\cdot}8$

or $y = 450 + 61{\cdot}8\sqrt[3]{x - 1}$.

§ 279. **Setting Time.**—There is a distinction between setting and hardening. The initial setting is the commencement of the chemical action which occurs when the water combines with the cement, hardening is a much slower process. As a disturbance of the setting process may produce a loss of strength it is desirable that the initial setting is not interrupted and that the whole

operation of mixing and moulding should be completed before the cement begins to set.

The initial setting time is the time which elapses from the moment water is added until the paste ceases to be fluid and plastic. For the B.E.S.A. specification the time is taken from the moment that the special mould is filled with the gauged cement, and not from the time that water is added to the cement.

The final set is acquired when the material attains a certain degree of hardness.

The B.E.S.A. specification of 1920 recognises two distinct graduations of time of setting, viz. :—

Grade.	Initial Setting Time. In Minutes.	Final Setting Time.
Quick	Not less than 2	Not greater than 30 mins.
Slow	„ „ „ 20	„ „ „ 10 hours

The test block for setting time is made in a special mould (80 mm. diameter and 40 mm. high) (N, Fig. 256) and filled with neat cement mixed and gauged in the manner described for tensile tests.

The time of initial setting is determined empirically by the time taken, after filling the mould, for a weighted needle to cease to pierce the test block completely. The B.E.S.A. specification has decided on a special apparatus for carrying out this test called the " Vicat " needle (B, Fig. 256). The needle is 1 mm. square in section with a flat end, and the total weight of needle and attachments is 300 grammes. The apparatus is fitted with a device for measuring the depth of penetration of the needle.

The final setting time is determined empirically by the same apparatus but using a slighly different form of needle. A needle of the same section as before projects 0·5 mm. beyond a hollowed out circular cutting edge (5 mm. in diameter). The final setting time is taken as that when the needle makes an impression but the circular attachment fails to do so.

The setting times are affected by the temperature of the mixing water, the percentage of water used, and the temperature and humidity of the air. It is preferable for the tests to be conducted in moist air.

§ 280. **Soundness or Constancy of Volume.**—A cement which remains perfectly sound is said to be of constant volume.

Failure is shown by cracking, swelling, blowing or disintegration. To ascertain the soundness of Portland cement a rough test is to make a pat of cement ½ inch thick, gauged with 25 per cent. by weight of clean water, on non-porous material preferably glass. This is placed in water at 16° C. after twenty-four hours in moist air, and left there for inspection at intervals; it should show no signs of failure.

This test is sometimes accelerated by exposing a pat of the cement for five hours, in an atmosphere of steam, to a temperature of 98° C. to 100° C.

The test specified by the B.E.S.A. is the Le Chatelier test. This is made in the apparatus shown in Fig. 258 and D, Fig. 256, which consists of a small split cylinder of brass (0·5 mm. thick) forming a mould 30 mm. internal diameter and 30 mm. high. On either side of the split two indicators with pointed ends are

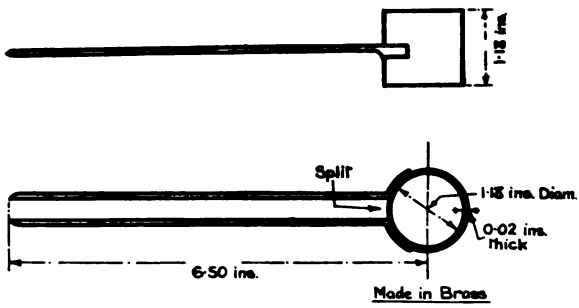

FIG. 258.—Le Chatelier test mould for soundness of cement.

attached. The distance from the ends of the indicators to the centre of the cylinder is 165 mm.

The Le Chatelier test has been accepted unreservedly in England, and the International Association of Testing Materials [6] decided to recommend the method as the standard accelerated test for constancy of volume of cements. The method is to be carried out as follows :—

"The cement is gauged and filled into the mould on a plate of glass, the edges of the mould being held together. When the mould has been filled it is covered with a plate of glass held down by a small weight, and the whole is immersed in water at 15° C. for twenty-four hours. Any tie or band which has been used to keep the edges of the mould together during setting time is then removed. The distance between the indicator needles is then measured and the mould is placed in cold water which is raised

to a temperature of 100° C. in the course of half an hour and is kept boiling for six hours. The mould is removed from the water and after it has cooled the distance between the indicator needles is again measured. The difference between the two measurements represents the expansion of the cement. This must not exceed 10 mm. when the cement has been aerated for twenty-four hours, and 5 mm. when the cement has been aerated for seven days."

§ 281. **Effect of Storage of Cement on the Strength of Concrete.**—Abrams [7] finds that the effect of storage of cement on the strength of concrete or mortar is largely a question of the age at which concrete or mortar is tested. The storage period and the age of the concrete or mortar at the time of testing are of greater importance than the exact condition of storage, so long as the cement is protected from direct contact with moisture.

The deterioration of cement in storage appears to be due to absorption of atmospheric moisture, causing a partial hydration, which exhibits itself in reducing the early strength of the concrete and prolonging the time of setting.

Compression tests of concrete and mortar show a deterioration in strength with storage of cement for all samples, for all conditions and periods of storage and at all test ages.

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[1] British Engineering Standards Association, "British Standard Specification for Portland Cement," Report No. 12.

[2] American Society for Testing Materials, "Standard Specification and Tests for Portland Cement," Specification No. C 9-17.

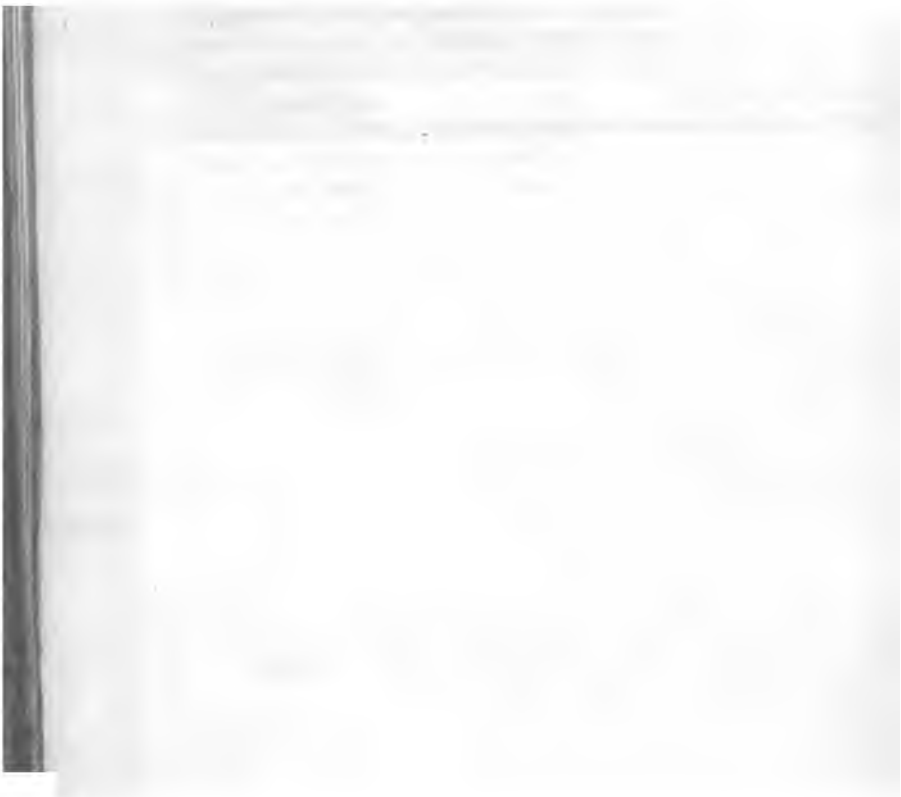
[3] Abrams, "Effect of Fineness of Cement," "American Soc. Test. Mat. Proc.," 1919, Vol. XIX, Pt. II, p. 328.

[4] Coker, "The Distribution of Stress at the Minimum Section of a Cement Briquette," "Inter. Assoc. Test. Mat. Proc.," 1910-13, Vol. II, Pt. II, paper xxviii$_4$.

[5] Unwin, "Testing of Materials of Construction," 1910 edition, p. 459.

[6] Blount, "On Accelerated Tests of the Constancy of Volume of Cements," "Inter. Assoc. Test. Mat. Proc.," 1909, 5th Congress, paper x$_3$.

[7] Abrams, "Effect of Storage of Cement," "Minutes of Spring Meeting of the Portland Cement Association," April, 1920, and Structural Materials Research Laboratory, Chicago, Bulletin No. 6, June, 1920.



APPENDIX.

LIST OF BRITISH STANDARD SPECIFICATIONS AND REPORTS.

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Nos. 5, 17, 19, 20, 22, 25, 26, 33, 34, 36, 38, 39, 49, 52, 60, 85.

Reports marked "Under Revision" are not available.

Report No.	
1—1920.	Rolled Sections for Structural Purposes, Lists of.
2—1903.	Tramway Rails and Fishplates, Specification and Sections of.
3—1903.	Influence of Gauge Length and Section of Test Bar on the Percentage of Elongation, Report on. By Professor W. C. UNWIN, F.R.S.
4—1921.	Channels and Beams for Structural Purposes, Dimensions and Properties of.
6—1904.	Rolled Sections for Structural Purposes, Properties of. *Under Revision*
7—1919.	Copper Conductors, Insulated Annealed for Electric Power and Light, Dimensions of.
8—1904.	Tramway Poles, Specification for Tubular.
9—1909.	Railway Rails, Specification and Sections of Bull Head.
10—1904.	Pipe Flanges, Tables of.
11—1909.	Railway Rails, Specification and Sections of Flat Bottom.
12—1920.	Portland Cement, Specification for.
13—1910.	Steel for Shipbuilding, Specification for Structural.
14—1907.	Steel for Marine Boilers, Specification for Structural.
15—1912.	Steel for Bridges, etc., and General Building Construction, Specification for Structural.
16—1905.	Telegraph Material, Specifications for. *Under Revision*
18—1910.	Tensile Test-pieces, Forms of.
21—1909.	Pipe Threads for Iron or Steel Pipes and Tubes, Report on.
23—1905.	Trolly Groove and Wire, Standards for.

Report No.

24 —— Railway Rolling Stock, Specifications for Material used in the Construction of.

24 Part I.—1921. Locomotive, Carriage and Wagon Axles (containing Specifications Nos. 1, 2, 2a, 3, 3a).

24 Part II.—1921. Locomotive, Carriage and Wagon Tyres (containing Specifications Nos. 4, 5, 5a).

24 Part III.—1921. Laminated, Volute and Helical Springs, and Steel for Laminated Springs (containing Specifications Nos. 6, 6a, 6b, 6c, 7, 7a).

24 Part IV.—1921. Steel Forgings, Blooms and Castings (containing Specifications Nos. 8, 9, 10).

24 Part V.—1911. Copper Plates, Rods and Tubes, and Brass Tubes (containing Specifications Nos. 11, 12, 13, 14, 15).

24 Part VI.—1921. Steel Plates, Angles, etc., and Rivets for Locomotives, Carriages and Wagons (containing Specifications Nos. 16, 17, 17a, 18, 18a).

27—1906. Limit Gauges for Running Fits, Report on Standard Systems of.

28—1908. Nuts, Bolt Heads and Spanners, Report on.

29—1909. Steel Forgings for Marine Purposes, Specification for Ingot.

30—1907. Steel Castings for Marine Purposes, Specification for.

31—1910. Steel Conduits for Electrical Wiring, Specification for.

32—1921. Steel Bars for the production of Machined Parts, Specification for.

35—1907. Copper Alloy Bars, for use in Automatic Machines, Specification for.

37—1919. Electricity Meters, Specification for.

40—1908. Cast-iron Low Pressure Heating Pipes, Specification for Spigot and Socket.

41—1908. Cast-iron Flue or Smoke Pipes, Specification for Spigot and Socket.

42—1908. Steam Engines for Electrical Purposes, Report on Reciprocating. *Under Revision*

43—1909. Boiler Tubes, Specification for Charcoal Iron Lapwelded.

44—1909. Cast-iron Pipes for Hydraulic Power, Specification for.

45—1917. Sparking Plugs (for Internal Combustion Engines), Dimensions for.

46—1909. Keys and Keyways, Specification for.

47—1919. Steel Fishplates, for Bull Head and Flat Bottom Railway Rails, Specification and Sections of.

48—1909. Wrought Iron of Smithing Quality for Shipbuilding (Grade D), Specification for.

50—1910. Locomotives for Indian Railways, Third Report on (superseding Nos. 5 and 26). *Under Revision*

51—1913. Wrought Iron, for use in Railway Rolling Stock ("Best-Yorkshire" and Grades A, B and C), Specification for.

53—1913. Boiler Tubes for Locomotive Boilers, Specification for Cold Drawn Weldless Steel.

54—1911. Screw Threads, Nuts and Bolt Heads for use in Automobile Construction, Report on.

55—1911. Copper and Bronze Wire, Report on Hard Drawn.

56—1911. Yield Point and Elastic Limit, Definitions of.

57—1920. Heads for British Association Screws, Report on.

Report No.

58—1912. Cast-iron Soil Pipes, Specification for Spigot and Socket.
59—1912. Cast-iron Waste and Ventilating Pipes (for other than Soil Purposes), Specification for Spigot and Socket.
61—1913. Copper Tubes and their Screw Threads (primarily for domestic and similar work), Specification for.
62—1913. Marine Boiler Stays, Screwing for.
63—1913. Broken Stone and Chippings, Specification for Sizes of.
64—1913. Fishbolts and Nuts for Railway Rails, Specification for.
65—1914. Salt-glazed Ware Pipes, Specification for.
66—1914. Copper Alloy Three-piece Unions (for Low and Medium Pressure Screwed Copper Tubes), Specification for.
67—1914. Ceiling Roses, Specification for Two- and Three-plate.
68—1914. Steel Conductor Rails, Method of Specifying the Resistance of.
69—1915. Tungsten Filament Glow Lamps (Vacuum Type) for Automobiles, Report on.
70—1915. Pneumatic Tyre Rims for Automobiles, Motor Cycles and Cycles, Report on. *Under Revision*
71—1917. Wheel Rims and Tyre Bands for Solid Rubber Tyres for Automobiles, Report on Dimensions of. *Under Revision*
72—1917. Electrical Machinery, British Standardisation Rules for.
73—1919. Two-pin Wall Plugs and Sockets, Specification for.
74—1917. Charging Plug and Socket, for Vehicles propelled by Electric Secondary Batteries, Specification for.
75—1916. Steels for Automobiles, Specifications for Wrought.
76—1916. Tars, Pitches, Bitumens and Asphalts when used for Road Purposes, Report on Nomenclature of, and Specifications for Tar and Pitch for Road Purposes.
77—1921. Electrical Pressures for New Systems and Installations.
78—1917. Cast-iron Pipes and Special Castings for Water, Gas and Sewage, Specification for.
79—1919. Special Trackwork for Tramways, Report on British Standard.
80—1917. Magnetos for Automobile Purposes, Report on Dimensions of. *Under Revision*
81—1919. Instrument Transformers, Specification for.
82—1919. Starters for Electric Motors, Specification for.
83—1918. Dope and Protective Covering for Aircraft, Standard of Reference for.
84—1918. Screw Threads, British Standard Fine and their Tolerances (superseding parts of Reports Nos. 20 and 38), Report on.
86—1919. Magnetos for Aircraft Purposes, Report on Dimensions of.
87—1919. Air Screw Hubs, Report on Dimensions of.
88—1919. Electric Cut-outs. Low Pressure (Type O), Specification for.
89—1919. Indicating Ammeters, Voltmeters, Wattmeters, Frequency and Power Factor Metres, Specification for.
90—1919. Recording (Graphic) Ammeters, Voltmeters and Wattmeters, Specification for
91—1921. Electric Cable Soldering Sockets, Specification for.
94—1920. Watertight Glands for Electric Cables, Specification for.
95—1919. Corrections to Effective Diameter required to Compensate Pitch and Angle Errors in Screw Threads of Whitworth form, Tables of.

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97—1920. Watertight Fittings for Incandescent Electric Lamps, Specification for.
98—1919. Goliath Lamp Caps and Lamp Holders, Specification for.
100—1920. Body Spaces and Frame Ends for Chassis for Private Automobiles, Dimensions for.
101—1921. Tramway Tyres, Specification for.
102—1921. Tramway Axles, Specification for.
103—1919. Falling Weight Testing Machines for Rails, Specification for.
104—1919. Light Flat Bottom Railway Rails and Fishplates, Sections of.
105—1919. Light and Heavy Bridge Type Railway Rails, Sections of.
106—1920. Electrically Heated Cooking Range (Two sizes), Specification for.
107—1919. Rolled Sections for Magnet Steel.
109—1921. Air-break Knife Switches and Laminated Brush Switches for Pressures not exceeding 660 Volts, Specification for.
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111—1920. Wrought Steels for Aircraft, Schedule of.
112—1920. Cold Worked Steels for Aircraft, Schedule of.
113—1920. Sheet Steels for Aircraft, Schedule of.
114—1920. Valve and Valve Spring Steels for Aircraft, Schedule of.
115—1921. Metallic Resistance Materials for Electrical Purposes, Specification for.
122—1920. Milling Cutters and Reamers, Standards for.
131—1920. Notched Bar Test-pieces, Forms of.
132—1920. Steam Turbines for Electrical Plant, Specification for.
133—1921. Normal Type Vacuum Tungsten Filament Electric Lamps, Specification for.
135—1921. Benzol for Motor Fuel, Specification for.
136—1920. Automatic Telephone Systems, Terms and Definitions for use in connection with.
139—1921. Red Fir Wood Poles for Telegraph and Telephone Lines, Specification for.
144—1921. Creosote for the Preservation of Timber, Specification for.
145—1921. Condenser Tubes and Screwed Glands for Condensers and Marine Purposes, Specification for.

INTERIM REPORT.

C.L. 2582. Ball Journal Bearings for Automobiles, Interim Report on Sizes of Single Row.
C.L. 3750. French Metric Screw Threads for Aircraft Purposes, Interim Report on.
C.L. 7270. Screw Threads, British Standard Whitworth and their Tolerances (superseding Nos. 20 and 38), Interim Report on.
C.L. 7271. Screw Threads, British Association with Tolerances for sizes Nos 0 to 15 B.A. (superseding No. 20), Interim Report on.
C.L. 8564—1920. Rubber Tyres for British Standard Rims, List of.

Reports marked " Under Revision " are not available.

FOREIGN TRANSLATIONS.

A number of the Specifications and Reports of the Association are being issued in French, Italian, Portuguese and Spanish. The English Editions and the Foreign Translations (which also include the English Text) are being published in octavo form at 1s. net per copy or its equivalent in foreign moneys.

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12—1920.	Portland Cement, Specification for.
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14—1907.	Steel for Marine Boilers, Specification for Structural.
15—1912.	Steel for Bridges, etc., and General Building Construction, Specification for Structural.
29—1909.	Steel Forgings for Marine Purposes, Specification for Ingot.
37—1919.	Electricity Meters, Specification for.
72—1917.	Electrical Machinery, British Standardisation Rules for.

ITALIAN.

13—1910.	Steel for Shipbuilding, Specification for Structural.
14—1907.	Steel for Marine Boilers, Specification for Structural.
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* An Addendum Slip is issued with this Translation showing the modifications necessitated by the revision of the English edition of this Specification.

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